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INITIAL FOOT CONTACT PATTERNS IN SHOD RUNNING, RELATIONSHIP WITH SPEED AND IMPACT INTENSITY

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Thesis submitted in fulfillment of the requirements for the degree of

doctor of Health Sciences

dedicated to

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and

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SUMMARY

Background

Running styles are most commonly categorized based on the part of the foot that makes initial contact with the ground. As such, an initial rear- , mid- or forefoot contact are possible. The most common method to determine these initial foot contact patterns (IFCP) is the strike index method. This method uses force plate data to locate the center of pressure point on the foot at initial foot contact. This method could be optimized by using measuring systems that can more accurately determine the center of pressure at low ground reaction forces. At submaximal running speed, most runners perform an initial rearfoot contact pattern (IRFC). At faster running speeds, the number of initial mid- (IMFC) and forefoot contact patterns (IFFC) increases. However, the intra-individual relation between running speed and IFCP is still unknown.

Different IFCPs have been related with differences in impact intensity which is relevant for stress fracture injury susceptibility. If IFCPs are indeed related to impact intensity, there must be some kinematic differences between the different patterns. Research demonstrated that the different patterns are related to differences in the foot position at initial contact, so there will be at least some distal ankle and foot kinematic differences. As different initial touch down positions induce marked differences in the following foot unroll, e.g. heel strikers versus forefoot strikers, kinematics and kinetics during the entire foot unroll are studied. The kinematic differences and their relation with impact intensity might provide new insights in the mechanics of impact and the kinematic 'strategies' to reduce impact intensity.

Also the kinetics, such as the spatial distribution of the impact intensity over different zones under the foot, will differ between different IFCPs. Useful indications for IFCP specific instructions on passive cushioning in running footwear will be deduced.

In the first chapter of this thesis, the introduction, we provide an overview of the basic biomechanics of distance running, the characterisation of running styles based on IFCP and the impact intensity in running. Also the gaps in the literature, that have led to the research questions addresses in this thesis, are presented.

Purpose

This thesis aims at a better understanding of the relation between IFCP and running speed and between IFCP and impact intensity. The different studies aimed to answer the following research questions (Q):

> Q1. Can we accurately assess strike index (and IFCP) at initial foot contact during constant pace shod running?
> Q2. What is the within-subject effect of running speed on initial foot contact pattern?
> Q3. What are the kinematic differences between the different IFCPs?
> Q4. What is the difference in impact intensity between the different IFCPs?
> Q5. What is the relationship between the observed kinematic differences between the different IFCPs and the impact intensity?
> Q6. Does the spatial distribution of the impact intensity over different foot zones differ in runners with different IFCPs?

An answer to these research questions is given in the three studies around which this thesis is built. In the first study we answer Q1, 2 and 4; in the second study we answer Q3, 4 and 5 and in the third study we answer Q6.

Methods

All data was collected during one large testing campaign. Fifty-five runners (40♂ and 15♀) of recreational and competitive level ran at four running speeds (3.2, 4.1, 5.1 and 6.2 $m \cdot s^{-1}$(11.5, 14.8, 18.4 and 22.3 $km \cdot h^{-1}$) over a 25m instrumented indoor running track. All runners wore the same shoes (Li Ning Magne), that were modified for optimizing plantar pressure measurements by substituting a flat outsole and filling in the midfoot region of the midsole with an EVA foam, so as to remove the cavity between the heel and forefoot part of the shoe. We recorded ground reaction forces to determine impact intensity, plantar pressures under the shoe to determine initial foot contact pattern and the spatial distribution of the ground reaction force and we recorded lower limb 3D kinematics.

Results and conclusions

Q1. Can we accurately assess strike index (and IFCP) at initial foot contact during constant pace shod running?

We have introduced a refined strike index method to determine IFCP, based on high speed plantar pressure measurements that give the accurate location of the COP at the very first instant of initial contact. The measurement of the time until first metatarsal contact after initial contact and the interpretation of the initial trajectory of the COP allowed to discern Typical and a previously unknown Atypical IRFC. These Atypical IRFC showed a fast initial anterior displacement of the COP along the lateral shoe margin into the midfoot zone and an early first metatarsal contact. Also IMFC and IFFC were categorized. We found that most runners perform an IRFC. At a pace close to training velocity (3.2 $m \cdot s^{-1}$) the distribution within our subject group was 58% Typical IRFC, 24% Atypical IRFC, 18% IMFC and no IFFC.

Q2. What is the within-subject effect of running speed on initial foot contact pattern?

IFCP is influenced by speed as of 45% of subjects transitioned towards a more anterior located (IMFC or IFFC) IFCP with increasing speed. Nevertheless, 46% remained IRFC and 6% IMFC over all tested running speeds.

Q3. What are the kinematic differences between the different IFCPs?

Both differences in distal ankle and foot kinematics as in global running style indicated that Typical IRFC, Atypical IRFC and IMFC/IFFC are considerably different running styles. The main kinematic differences between the different IFCP are situated at the foot and ankle during the initial foot contact phase. Runners with a Typical IRFC make initial contact with the ground with a slightly dorsiflexed ankle, a posteriorly inclined foot position and a more posteriorly inclined leg angle (metatarsals to hip). The Atypical IRFC make initial contact with the ground with a nearly ‘flat’, slightly posteriorly inclined foot position. The IMFC/IFFC make initial contact with the ground with a slightly plantar flexed ankle and a nearly ‘flat’ or slightly anteriorly inclined foot position. Also, through a greater knee flexion range of motion, the Typical IRFC have longer contact times than the other IFCP. No differences in step frequency were found between the different IFCPs.

Q4. What is the difference in impact intensity between the different IFCPs?

The Atypical IRFC showed the highest impact intensity while the IMFC/IFFC showed the lowest impact intensity. This is relevant as a higher impact intensity has been linked to an increased stress fracture injury susceptibility.

Q5. What is the relationship between the observed kinematic differences between the different IFCPs and the impact intensity?

Different IFCPs use different impact reducing kinematic strategies. Typical IRFC use an initial ankle plantarflexion and the cushioning properties of the heel fat pad and heel part of the shoe while IMFC/IFFC use an initial ankle dorsiflexion. The observed higher loading rates of the ground reaction force (~higher impact intensity) in the Atypical IRFC could be explained by both global running style (shorter contact times and greater leg stiffness) and distal ankle and foot kinematics (flatter foot at initial foot contact followed by a limited ankle plantar flexion) that indicate a limited use of known kinematic impact reducing 'strategies' such as initial ankle dorsiflexion in IMFC/IFFC and initial ankle plantar flexion in Typical IRFC. The common belief that pronounced 'heel striking' induces the greatest loading rates of the vertical ground reaction force should be reconsidered. Moreover, caution should be exercised when training to transition from a Typical IRFC to an IMFC/IFFC because one might end up in an Atypical IRFC, which might be hard to discern from an IMFC without the use of specified measurements and which might cause an increased impact intensity. This is again relevant as higher loading rates have been linked with an increased stress fracture injury risk.

Q6. Does the spatial distribution of the impact intensity over different foot zones differ in runners with different IFCPs?

IFCP is related to the impact intensity and the spatial distribution of the impact intensity over the different foot zones. The impact intensity is mainly situated under the rearfoot and midfoot for the Typical IRFC, under the midfoot for the Atypical IRFC and under the midfoot and forefoot for the IMFC/IFFC. These findings indicate that for passive impact intensity reduction the different IFCPs would benefit from cushioning in different zones of the shoe sole.

Apart from answering the specific research questions, the general discussion of this thesis elaborated primarily on a better understanding of the biomechanics of impact in distance running. Additionally to the analyses in the studies, an analysis of the segmental (foot, shank, thigh, …) contributions to the vertical ground reaction force has been performed. Such analysis has not been done before in different IFCPs and should provide mechanical 'proof' of impact intensity differences between the different IFCPs. However, the results of the analysis were only partially able to explain the impact intensity differences between the different IFCPs. Such analysis, in which kinematic data is used to calculate kinetic data, remains challenging due to methodological limitations and difficulties. Also joint moment, work and power were calculated and compared between the different IFCPs. This analysis has shown that IFCP is related to loading of the extensor muscles crossing ankle and knee. Running with a Typical IRFC showed the highest eccentric extensor power at the knee, while running with an IMFC/IFFC showed the highest eccentric plantar flexion power at the ankle joint, which confirms previous research. These findings are relevant for runners who want to change their running style in order to influence the loading of the extensor muscles at the ankle or knee.

Although our studies provided an answer to the research questions, also several future research questions (FRQ) have been formulated:

FRQ1. What are the individual determinants for a certain IFCP?

FRQ2. Why does IFCP change with increasing speed?

FRQ3. What is the within-subject relation between running kinematics and impact intensity?

FRQ4. Can IFCP-specific shoe design cushion impact intensity?

FRQ5. Is IFCP related to running performance?

SAMENVATTING

Achtergrondinformatie

Loopstijlen worden vaak ingedeeld op basis van het deel van de voet waarmee het eerste contact met de grond wordt gemaakt. Zo is een achter-, midden- of voorvoet raakpatroon mogelijk. De meest gebruikte methode om deze initiële voet raakpatronen te bepalen is de strike index methode. Deze methode gebruikt data uit een krachtmeetplatform om bij initieel contact het drukmiddelpunt op de voet te lokaliseren. Deze methode kan geoptimaliseerd worden door gebruik te maken van meetsystemen die een nauwkeurigere bepaling van het drukmiddelpunt toelaten bij kleine grondreactiekrachten. Aan submaximale loopsnelheden vertonen de meeste lopers een achtervoet raakpatroon (AVRP). Bij hogere loopsnelheden, neemt het aandeel van lopers met een middenvoet (MVRP) of voorvoet raakpatroon (VVRP) toe. De intra-individuele relatie tussen loopsnelheid en raakpatroon is echter nog niet gekend.

Verschillende raakpatronen werden gerelateerd aan verschillen in impactintensiteit, wat relevant is in functie van het risico op het ontwikkelen van stressfracturen. Als raakpatronen inderdaad gerelateerd zijn aan impactintensiteit moeten er wel enkele verschillen zijn in de kinematica van de verschillende raakpatronen. Onderzoek heeft reeds aangetoond dat de verschillende raakpatronen een verschil in voetpositie vertonen op het moment van initieel contact, dus zullen er op zijn minst enkele verschillen zijn in de distale kinematica van de enkel en de voet. Aangezien verschillende initiële raakpatronen aanleiding geven tot verschillen in de verdere voetafrol, vb. achtervoet versus voorvoet lopers, werden in deze thesis de kinematica en kinetica tijdens de volledige voetafrol bestudeerd. De verschillen in de kinematica tussen de verschillende raakpatronen en hun relatie met impactintensiteit kunnen leiden tot nieuwe inzichten in de biomechanica van impact en de kinematische ‘strategieën’ om impact te beperken.

Ook de kinetica (=krachtwerking), zoals de ruimtelijke spreiding van de impactintensiteit over de verschillende zones onder de voet, zal verschillen bij de verschillende raakpatronen. Praktische richtlijnen voor het ontwikkelen van raakpatroon-specifieke passieve impactreductie in loopschoeisel zullen afgeleid worden.

In het eerste deel van deze thesis, de introductie, wordt een overzicht gegeven van de basis biomechanica van afstandslopen, de classificatie van loopstijlen gebaseerd op raakpatroon en de impactintensiteit van lopen.

Doelstellingen

Deze thesis doelt op het verschaffen van nieuwe inzichten in de relatie tussen raakpatroon en loopsnelheid en raakpatroon en impactintensiteit. De verschillende studies zullen een antwoord proberen te geven op de volgende onderzoeksvragen (V):

V1. Kunnen we strike index (en raakpatroon) accuraat bepalen op het tijdstip van initieel voetcontact tijdens geschoeid lopen aan constante snelheid?
V2. Wat is het intra-subject effect van loopsnelheid op het raakpatroon?
V3. Wat zijn de verschillen in de kinematica van de verschillende raakpatronen?
V4. Wat is het verschil in impactintensiteit tussen de verschillende raakpatronen?
V5. Wat is de relatie tussen de waargenomen verschillen in kinematica en de verschillen in impactintensiteit tussen de verschillende raakpatronen?
V6. Verschilt de ruimtelijke spreiding van de impactintensiteit over de verschillende zones onder de voet tussen de verschillende raakpatronen?

De drie studies waarrond deze thesis is opgebouwd geven een antwoord op deze onderzoeksvragen. In de eerste studie beantwoorden we V1, 2 en 4; in de tweede studie V3, 4 en 5 en in de derde studie V6.

Methodes

Alle data werd verzameld tijdens een grote testcampagne. Vijfenvijftig lopers (40♂ en 15♀) van recreatief en competitief niveau liepen aan vier loopsnelheden (3.2, 4.1, 5.1 en 6.2 $m \cdot s^{-1}$) (11.5, 14.8, 18.4 en 22.3 $km \cdot h^{-1}$) over een geïnstrumenteerde indoor loopweg van 25m. Alle lopers droegen dezelfde schoenen (Li Ning Magne), die bijgewerkt werden om plantaire drukmetingen te optimaliseren door ze een vlakke zool te geven en de middenvoet zone op te vullen met een

EVA schuim, zodat er geen holte meer was tussen het achtervoet en voorvoet deel van de schoen. Tijdens de looptrials registreerden we grondreactiekrachten om de impactintensiteit te bepalen, plantaire druk onder de schoen om het initieel raakpatroon en de ruimtelijke spreiding van de grondreactiekrachten te bepalen en registreerden we 3D kinematica van de onderste ledematen.

Resultaten en conclusies

V1. Kunnen we strike index (en raakpatroon) accuraat bepalen op het tijdstip van initieel voetcontact tijdens geschoeid lopen aan constante snelheid?

We hebben een verfijnde strike index methode geïntroduceerd om raakpatronen te bepalen, gebaseerd op hoog frequente metingen van plantaire druk die toelaten om de locatie van het drukmiddelpunt op de voet accuraat te bepalen op het moment van initieel voetcontact. Het bepalen van de tijd tot het eerste metatarsaal contact en de interpretatie van het initiële traject van het drukmiddelpunt lieten toe om Typische en de voordien ongekende Atypische achtervoet raakpatronen (AVRP) te onderscheiden. De Atypische AVRP vertoonden een snelle anterieure verplaatsing van het drukmiddelpunt langs de laterale rand van de schoen naar de middenvoet zone en een vroeg eerste metatarsaal contact. Ook MVRP en VVRP werden bepaald. De meeste lopers vertoonden inderdaad een AVRP. Aan een loopsnelheid rond trainingssnelheid ($3.2\ m \cdot s^{-1}$) was de verdeling binnen onze proefgroep 58% Typisch AVRP, 24% Atypisch AVRP, 18% MVRP en geen VVRP.

V2. Wat is het intra-subject effect van loopsnelheid op het initieel raakpatroon?

Raakpatroon is gerelateerd aan loopsnelheid aangezien 15% van de lopers een transitie vertoonden naar een meer anterieur raakpatroon wanneer de loopsnelheid toeneemt (vb. van AVRP naar MVRP). Desalniettemin vertoonde 46% een AVRP en 6% een MVRP overheen alle loopsnelheden.

V3. Wat zijn de verschillen in de kinematica van de verschillende raakpatronen?

Zowel verschillen in distale enkel en voet kinematica als verschillen in globale loopstijl tonen aan dat Typisch AVRP, Atypisch AVRP en MVRP/VVRP duidelijk verschillende loopstijlen zijn. De voornaamste kinematische verschillen zijn gesitueerd ter hoogte van de enkel en de voet tijdens de initiële fase van het voetcontact. Lopers met een Typisch AVRP maken initieel contact met de grond met een lichte dorsiflexie in de enkel, een naar achteren gekantelde voet en een meer naar achteren gekantelde totale beenhoek (metatarsalen tot heup) dan de andere raakpatronen. De Atypische AVRP maken initieel contact met de grond met een bijna vlakke, lichtjes naar achteren gekantelde voet. De MVRP/VVRP maken initieel contact met een lichte plantair flexie in de enkel en een zo goed als vlakke of licht naar voor gekantelde voet. Bovendien vertonen de Typische AVRP langere contacttijden, samengaand met een diepere knieflexie tijdens contact, dan de andere raakpatronen. Tussen de raakpatronen werd geen verschil gevonden in stap frequentie. In deze studie werden de kinematische verschillen beschreven tussen de verschillende raakpatronen, in het bijzonder waarbij Typische en Atypische AVRP van elkaar werden onderscheiden, wat relevant is gezien het verschil in impactintensiteit tussen deze raakpatronen?

V4. Wat is het verschil in impactintensiteit tussen de verschillende raakpatronen?

De Atypische AVRP vertoonden de hoogste impactintensiteit, de MVRP/VVRP de laagste impactintensiteit. Dit is relevant aangezien een verhoogde impactintensiteit gelinkt wordt aan een verhoogd risico op de ontwikkeling van stressfracturen.

V5. Wat is de relatie tussen de waargenomen verschillen in kinematica en de verschillen in impactintensiteit tussen de verschillende raakpatronen?

De verschillende raakpatronen vertonen verschillende impact reducerende 'strategieën'. Typische AVRP maken gebruik van een initiële plantair flexie van de enkel en de dempende eigenschappen van het hiel vetweefsel en het achtervoet gedeelte van de schoen terwijl MVRP/VVRP gebruik maken van een initiële dorsiflexie van de enkel. De hogere belastingssnelheid van de grondreactiekracht (~hogere impactintensiteit) in de Atypische AVRP kan verklaard worden door zowel globale loopstijl (kortere contacttijden en grotere beenstijfheid) als distale enkel en voet kinematica (vlakkere voetpositie, gevolgd door zeer beperkte initiële plantair flexie van de enkel) die wijzen op een beperkt gebruik van de gekende kinematische impact reducerende 'strategieën' zoals initiële plantair flexie van de enkel bij Typische AVRP en initiële dorsiflexie van de enkel bij MVRP/VVRP. De algemene opvatting dat uitgesproken 'hiel' lopen (~AVRP) de grootste belastingssnelheid van de grondreactiekracht uitlokt moet herzien worden. Bovendien moet men voorzichtig zijn wanneer er specifiek getraind wordt op het omschakelen van een AVRP naar een MVRP. Men kan ongewild een Atypisch AVRP vertonen, wat moeilijk te onderscheiden valt van een MVRP zonder specifieke metingen, gezien de beperkte kinematische verschillen tussen deze raakpatronen, maar wel een verhoogde impactintensiteit kan uitlokken.

V6. Verschilt de ruimtelijke spreiding van de impactintensiteit over de verschillende zones onder de voet tussen de verschillende raakpatronen?

Raakpatroon is gerelateerd aan impact intensiteit en de ruimtelijke spreiding hiervan over de verschillende zones onder de voet. De impact intensiteit is vooral gesitueerd onder achter- en middenvoet zone bij de Typische AVRP, onder de middenvoet bij de Atypische AVRP en onder de midden- en voorvoet zone bij de MVRP/VVRP. Deze bevindingen tonen aan dat voor passieve impactreductie de verschillende raakpatronen impactreductie zouden kunnen bekomen met passieve demping in verschillende zones van de schoenzool.

Naast het beantwoorden van de specifieke onderzoeksvragen wordt er in de algemene discussie aandacht besteed aan hoe deze thesis heeft bijgedragen tot nieuwe inzichten in de biomechanica van impact in afstandslopen. Bovenop de analyses die uitgevoerd zijn in de besproken studies, werd een analyse uitgevoerd waarbij de bijdrage van de verschillende segmenten (voet, onderbeen, dij, ..) aan de verticale grondreactiekracht werd berekend. Een dergelijke analyse werd eerder nog niet gedaan voor verschillende raakpatronen en zou mechanisch ‘bewijs’ kunnen leveren voor het verschil in impact intensiteit tussen de verschillende raakpatronen. Deze analyse kon echter slechts deels de verschillen in impactintensiteit verklaren. Een dergelijke analyse, waarbij kinematica data gebruikt wordt om kinetica data te bereken, blijft uitdagend wegens methodologische beperkingen en moeilijkheden. Ook gewrichtsmoment, -arbeid en –vermogen van de knie en enkel werden berekend en vergeleken tussen de verschillende raakpatronen. Er werd aangetoond dat raakpatroon gerelateerd is aan belasting van de extensor spieren die het enkel- en kniegewricht overspannen. Bij het lopen met een Typisch AVRP situeert het hoogste excentrische vermogen zich ter hoogte van het kniegewricht, terwijl dit zich bij MCRP/VVRP ter hoogte van de enkel situeert, wat aansluit bij bevindingen uit eerder onderzoek. Deze bevindingen zijn relevant voor lopers die door middel van loopstijl adaptaties de excentrische belasting van de spieren rond knie- en/of enkelgewricht willen beïnvloeden.

Hoewel onze studies een antwoord hebben gegeven op de vooropgestelde onderzoeksvragen, kan ons onderzoek aanleiding geven tot het formuleren van toekomstige onderzoeksvragen (TOV):

TOV1. Wat zijn de individuele determinanten voor een bepaald raakpatroon?

TOV2. Waarom verandert raakpatroon met toenemende snelheid?

TOV3. Wat is de intra-subject relatie tussen kinematica en impactintensiteit?

TOV4. Kan raakpatroon-specifiek schoeisel impact intensiteit reduceren?

TOV5. Is raakpatroon gerelateerd aan loopprestatie?

GENERAL INTRODUCTION

1. PROLOGUE

Distance running has become a very popular leisure time activity. Even marathon running has changed from an elite running event to a mass recreational event. For instance, in 2014, 50530 runners participated in the New York city marathon with an average finishing time of 4:34:45. This can be seen as a positive evolution since running has beneficial effects on mental and physical health (e.g. cardiovascular risk factors). However, there is another side of the story. There is a very high rate of running related injuries. Reported incidence varies from 19 to 79% and incidence rates from 3 to 59 running related injuries per 1000 hours of running (44). Despite the multitude of studies, running footwear modifications and knowledge about modes of training the incidence remains high. By determining the risk factors and mechanisms of these injuries, preventive measures can be taken. The most determining risk factors are related to training modalities. Running too much, too fast makes you more prone to injuries (74). Increased impact intensity has been related to a retrospective occurrence of overuse injuries such as tibial stress fractures (55, 76, 108). Less convincing evidence exists for other biomechanical factors such as hyperpronation at the ankle joint, although relevant in a sports medical approach and frequently used as a base for running shoe prescription. Besides research on running injuries, also the Olympic motto '*citius, altius, fortius*' has been a stimulus for the biomechanical research in running performance determining factors. This thesis will focus on the biomechanics of distance running as opposed to sprint running.

In many of the distance running related research, runners are classified based on their initial foot contact pattern (IFCP) which could be a rear-, mid- or forefoot strike. IFCP has been related to differences in running economy (a performance determining factor for distance running) (89) and impact intensity (9) indicating the relevance of discerning different IFCPs. However, methodological improvements can be made in the determination of IFCP. Also the effect of running speed on IFCP and the relationship with impact related running kinematics are not yet fully understood. Therefore, this thesis will first provide an overview of the literature on distance running biomechanics, IFCP and running speed and IFCP and impact intensity. Second, the biomechanical studies that led to new insights in these topics will be described and discussed.

In the discipline of biomechanics researchers try to gain insights in the biology and mechanics of the human (and animal) body by applying the principles of mechanics. Many biomechanical research is conducted following the same scientific approach: measure, describe, analyze and integrate or assess (104). This implies that, after formulating hypothesis based on the current knowledge and gaps in the scientific literature all experimental biomechanical research starts with gathering data which will then be processed, analyzed and integrated. In the studies described in this thesis the raw data consists of kinetic data (ground reaction forces and plantar pressures) and 3D kinematic data (joint- and segment angles) of recreational and competitive runners running at speeds up to 6.2 $m \cdot s^{-1}$. The studies in this thesis will describe how these data were processed, analyzed and integrated to answer some research questions about the determination of IFCP, the relation between IFCP and running speed, the kinematic differences between different IFCPs and the relation between IFCP and impact intensity.

2. BASIC BIOMECHANICS OF DISTANCE RUNNING

2.1. Simple models simulating running biomechanics

While running, the lower limb muscle tendons and ligaments crossing the ankle and knee joint function as ideal springs. Each step they get stretched, storing elastic energy that is released during the push-off (61). This storage and release of elastic energy allows a lower mechanical work to be performed by the muscles and as such lowers the metabolic cost of running. During each foot contact the central nervous system matches the actions of the standing leg muscles with the elastic behavior of the tendons and ligaments, causing the musculoskeletal system to act as a mechanical linear spring. A simple planar spring-mass model, in which the total body mass is supported by a weightless linear spring, provides a good biomechanical (bio = elastic muscle-tendon complex of the support leg; mechanics = dynamics of the contact phase) representation of the contact phase in running (5, 72)(Fig. 1).

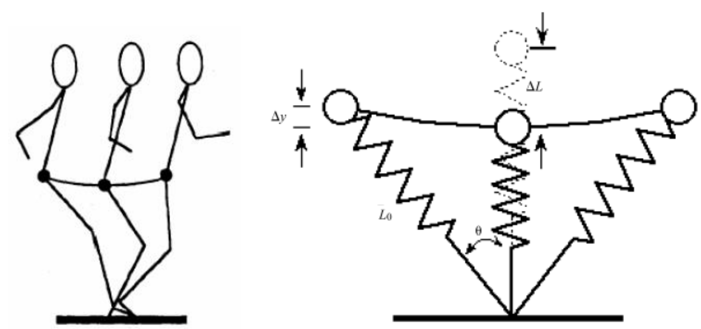

***Figure 1**: Adopted from Farley and Ferris 1998 and Farley 1993* (36, 39) *Spring-mass model during running. L_0= leg length at initial foot contact;Δy= vertical oscillation of the body center of mass; ΔL= leg compression; Θ=angle swept by the leg during half foot contact time.*

As the contact phase in running can be modelled as the bouncing of a linear spring, the mechanical characteristics of this spring can be used to describe the dynamics of the total body center of mass during a running foot contact. The mechanical behavior of a linear spring is most commonly described by calculating stiffness parameters. Stiffness can be defined as the ratio of the acting force to the deformation caused by this force. For the running gait, three types of mechanical/musculoskeletal quasi-stiffness (not the stiffness of an actual spring) are calculated:

Leg stiffness (k_{leg}): $k_{leg} = VGRF_{max}/\Delta L$

This parameter is the ratio of the peak vertical ground reaction force ($VGRF_{max}$) and the maximal leg compression (ΔL). The spring-mass model assumes that the instant of $VGRF_{max}$ and maximal leg compression coincide at midstance.

Vertical stiffness (k_{vert}): $k_{vert} = VGRF_{max}/\Delta y$

This form of stiffness does not describe the resistance to deformation of an actual physical spring, but determines the dynamics of the body center of mass. The vertical stiffness is the ratio of the peak vertical ground reaction force ($VGRF_{max}$) and the vertical oscillation of the body center of mass (Δy). The spring-mass model assumes that the instant of $VGRF_{max}$ and maximal vertical oscillation coincide at midstance.

Joint stiffness (k_{joint}): $k_{joint} = \Delta M_{joint}/\Delta \Theta_{joint}$

The leg stiffness is realized through the stiffness of the joints in the leg (ankle and knee). The joint stiffness describes the mechanical behavior of a joint as the ratio of the change in joint angular moment (M_{joint}) and the change in sagittal plane joint angle (Θ).

Several studies have been published which describe the effect of running speed (2, 12), running surface (38, 39, 59) or even footwear (34) on these stiffness parameters. In the second study described in this thesis we assessed these parameters for a group of distance runners and related them to running kinematics and impact intensity.

2.2. Spatio-temporal characteristics

Running speed is the result of stride length (SL) and stride frequency (SF). Therefore, both SL and SF are one of the basic parameters to describe the biomechanics of running. Also step frequency and step length can be used to describe the spatiotemporal characteristics of the running gait. A stride is defined from the initial contact of one foot until the following initial contact of the same foot. A step is defined from initial contact of one foot until initial contact of the other foot. As running distinguishes itself from walking by a flight phase, contact time (CT) and flight time (FT) are the final variables to describe the spatio-temporal characteristics of the running gait. Figures 2 A and B depict the evolution of SF, SL, CT and FT with increasing running speed. These spatio-temporal variables were assessed in the studies described in this thesis.

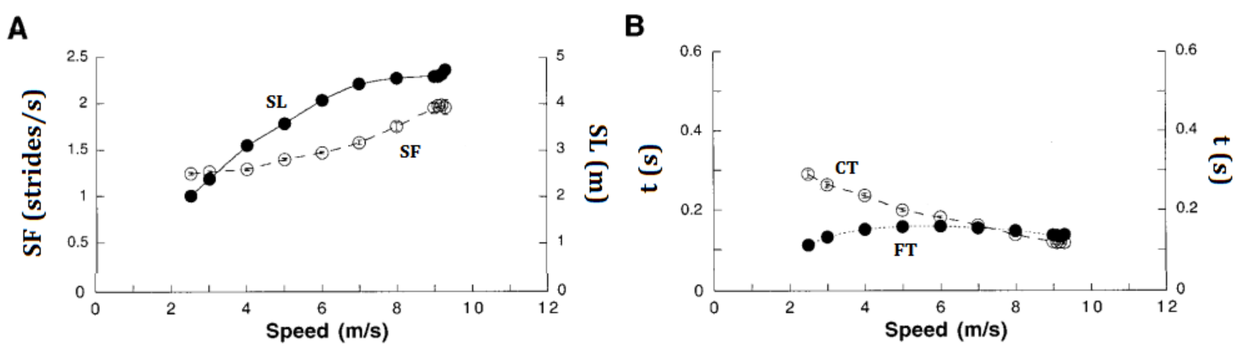

***Figure 2**: Adopted from Weyand et al.* (101)*: A. Stride length (SL) and stride frequency (SF) with increasing running speed. B. Contact time (CT) and flight time (FT) with increasing running speed. Subjects: 24 men and 9 women, physically active, between 18 and 36 years of age.*

2.3. Kinematics

2.3.1. Foot and ankle

Each foot contact the foot has to support the body and in doing so it has to fulfill an adaptive shock absorbing and supporting role. At first, these actions are realized by the motions of the subtalar and midtarsal joints (fig. 3).

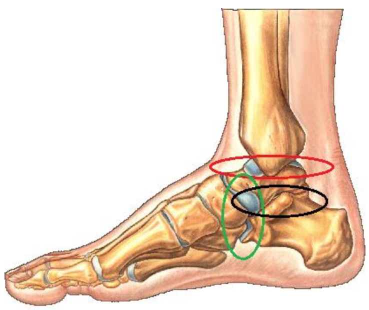

Figure 3*: Ankle (red oval = talo-crural joint, green oval = midtarsal joint, black oval = subtalar joint) and bones of the foot.*

In a normal heel-toe running foot unroll, immediately following initial foot contact there is an initial subtalar pronation that absorbs the impact through eccentric muscle activity. Moreover, the initial subtalar pronation unlocks the midtarsal joint (~navicular drop) causing the mid-forefoot to adopt a more flexible structure. This motion that is mainly situated in the frontal plane (subtalar eversion) is accompanied by an ankle joint plantar flexion in the sagittal plane. Example curves of these joint angle progressions during a foot contact are given in figure 4. Note that most people perform a heel-toe running foot contact (14, 50, 58, 60, 64) but other foot contact patterns are also possible. These will be described in '4. Initial foot contact pattern as a measure of running style'. The comparison of these different patterns forms the main topic of this thesis. For now, as a basis, we will describe the kinematics of the most common initial foot contact pattern heel-toe running. After the initial pronation and plantar flexion the foot reaches a 'foot flat' phase, subtalar pronation becomes maximal while the talo-crural joint shows a dorsiflexion. After the 'foot flat' phase the subtalar joint shows a resupination (subtalar inversion in the frontal plane) combined with a plantar flexion of the talo-crural joint propelling the body away from the ground. In the transverse plane the subtalar joint is in a slightly adducted (or internally rotated) position at initial foot contact. The initial pronation is then accompanied by an abduction (or external rotation) to reach its maximum at the 'foot flat' phase (~maximum pronation). During push-off the subtalar joint show a readduction (~resupination).

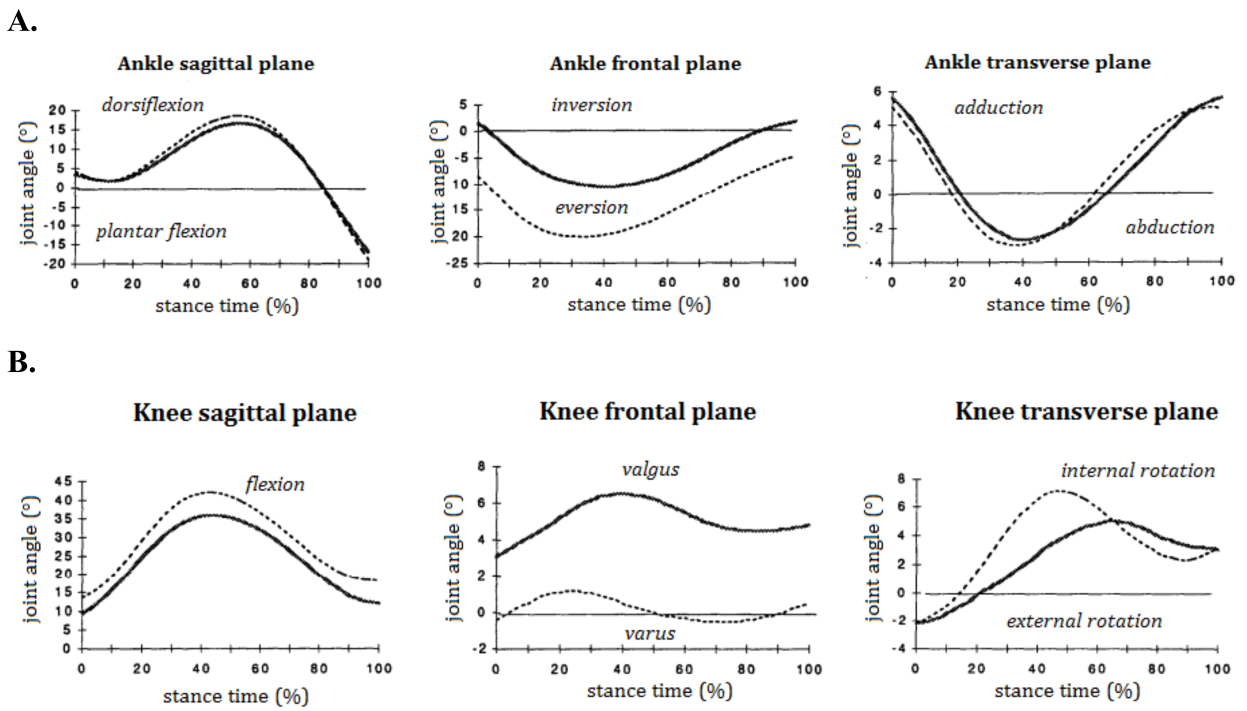

Figure 4: *Adopted from McClay and Manal* (70) *: Example curves of A. ankle joint and B. knee joint sagittal (left), frontal (middle) and transverse (right) plane movement. Solid lines represent a normal subject; dashed lines a subject with an elevated amount of ankle pronation. A zero value represents the joint stance in a relaxed standing position. Subjects were eighteen recreational runners between 18 and 40 years and data was collected during treadmill running at 3.35* $m \cdot s^{-1}$.

2.3.2. Knee joint

The movement of the knee joint has the greatest influence on the motion of the total body center of mass during the stance phase. At initial foot contact the knee is slightly flexed and immediately after initial foot contact the knee flexes to reach a maximum knee flexion around midstance, occurring after the 'foot flat' phase (fig. 4). After midstance the knee shows a re-extension to propel the body from the ground. In the frontal plane the knee shows a slight initial abduction valgus movement (~towards 'X- shaped' knees) flowed by an adduction varus motion (~away from 'X-shaped' knees). But the movement in the frontal plane is less pronounced compared to the sagittal plane knee movement. In the transverse plane the knee joint is in a slightly externally rotated position at initial contact. Until push-off is initiated, the knee joint shows an internal rotation (accompanying the knee flexion in the sagittal plane) after which a small re-external rotation occurs towards push-off. Example curves of the knee joint angle progressions during a foot contact are given in figure 4.

2.3.3. Hip joint

At initial foot contact the hip is slightly flexed and immediately after initial foot contact the hip slightly flexes to reach a maximum hip flexion around 30-35% of stance after which a re-extension follows to propel the body from the ground. In the frontal plane the hip shows a slight adduction movement followed by an abduction motion. But the movement in the frontal plane is less pronounced compared to the sagittal and frontal plane movement. In the transverse plane the hip joint is in a slightly internally rotated position at initial contact which evolves towards a more neutral position at push-off. Example curves of the knee joint angle progressions during a foot contact are given in figure 5.

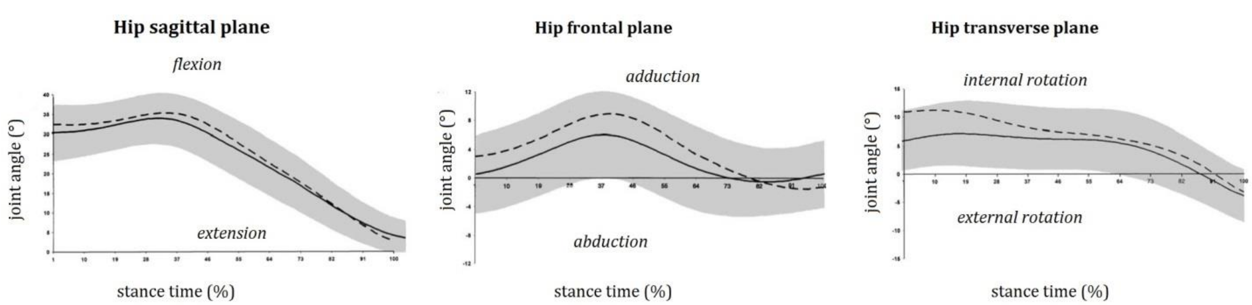

Figure 5*: Adopted from Ferber et al.* (37)*: Example curves of hip joint angles during stance phase of running. A zero value represents the joint stance in a relaxed standing position. Subjects were 20 male and 20 female recreational runners between 18 and 45 years and data was collected during overground running at 3.65 m·s^{-1}. Solid lines and shaded areas represent the mean ± SD values for the men, dashed lines the women.*

2.3.4. Phases of a foot unroll based on plantar pressures

Apart from the progress of the joint angles during foot contact, also the foot motion itself can be used to describe the temporal progress of a foot unroll. A study by De Cock *et al.* (23) indicated important time events during the foot unroll in barefoot jogging by young adults. These time events were detected based on plantar pressure data. An overview of the different time events and foot unroll phases is presented in figure 6.

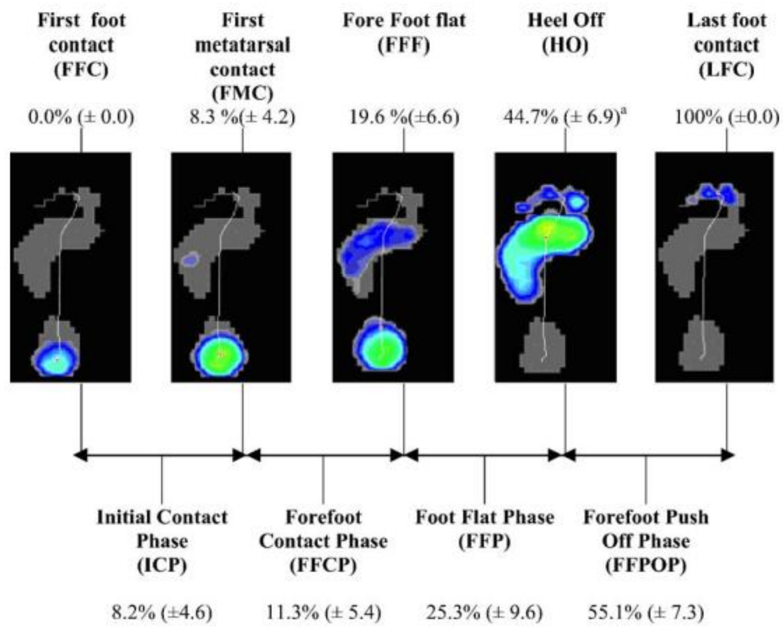

Figure 6: *Adopted from De Cock et al.* (23)*: Timing of important time events and phases relative to total foot contact time. Subjects were 220 healthy young adults running at 3.3* $m \cdot s^{-1}$ *over and indoor running track with a heel-toe running style.*

Note that these data were collected during barefoot running. As we know that footwear can alter running kinematics (34, 35, 99, 102) we expect that these time events and phases might slightly differ in shod running. Also all subjects were showing a heel-toe running style. Other running styles e.g. in which the forefoot makes initial contact with the ground are also possible. In such cases, first foot contact and first metatarsal foot contact would coincide.

In the second study of this thesis, frontal and sagittal plane ankle joint and sagittal plane knee joint angles were assessed and compared in a group of distance runners. In the first study in this thesis the time until first metatarsal foot contact was assessed during shod running and obtained as a submeasure to describe running style.

2.4. Ground reaction forces in distance running

The ground reaction forces (GRF) describe the force that the ground exerts on the running body during each step. The GRF can be represented and measured as a vector with a certain point of action, direction and magnitude and can be dissolved into three orthogonal components, mostly related to the running direction. The GRFs form the algebraic summation of the mass-acceleration products of all body segments while contacting the ground. As such the GRF contains the mechanical effect of each change in movement of all the segments during foot contact. Therefore, GRFs and derived variables are very important in biomechanical gait analysis. One of the most influential and frequently cited studies on GRFs in distance running was conducted by Cavanagh and Lafortune in 1980 (14). Figure 7 shows some example time-force curves of the vertical GRF component (VGRF).

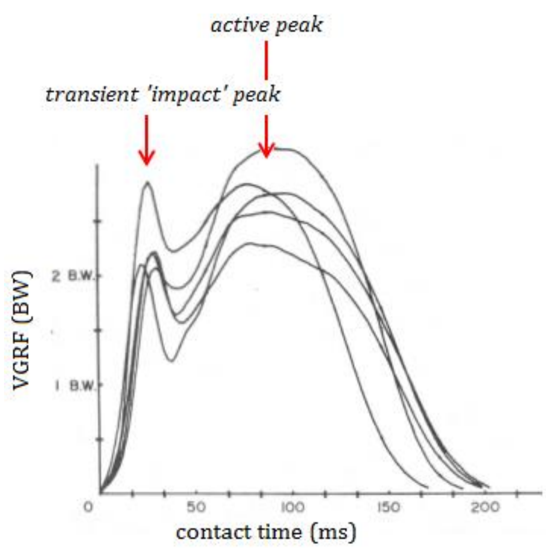

***Figure** 7: Adopted from Cavanagh and Lafortune* (14)*: Example time-VGRF curves of 5 selected heel-toe running trials with indication of the passive transient 'impact' peak and the active peak. VGRF is normalized to bodyweight (BW). Subjects were 17 competitive and recreational runners with a mean age of 24 years, running at about 4.5 m·s^{-1}.*

The typical shape the VGRF shows an initial passive transient impact peak within 0.050s following initial foot contact and an active peak around midstance with a magnitude up to 2-3 times bodyweight (BW). The transient impact peak has frequently been associated with the impact of the heel ‘striking’ the ground. However, Shorten *et al.* (95) have shown that this peak not only contains high frequency (>10Hz) force components but also has low frequency components (<10Hz) and that this force is not only originated from below the heel partition of the foot but also from more distal parts (midfoot and forefoot) of the foot.

Bobbert *et al.* (6, 7) have recomposed the VGRF signal based on the summation of the inertial terms (m·a) of the stance leg segmental and the rest of the body contributions. Their analysis showed that the timing of the initial transient peak indeed is caused by the deceleration of the distal masses, while the active peak more closely resembles the deceleration of the total body mass (Fig. 8). More recently, Clark *et al.* (20) conducted a study in which they modelled the VGRF based on following input variables: contact time, flight time, body mass (divided into 8% distal lower limb mass and 92% rest of body), vertical touchdown velocity of the lower limb (supposedly measured at the heel) and the time until the vertical velocity of the lower limb was zero. The model subdivided the VGRF into an impulse created by the deceleration of the distal mass and an impulse created by the deceleration of the rest of the body. The authors found surprisingly high degrees of correlation (R^2 range 0.95-0.98) between the modeled and measured signals (fig. 9). This indicated that the VGRF is indeed generated by a superimposition of both distal segment decelerations and the deceleration of the rest of the body.

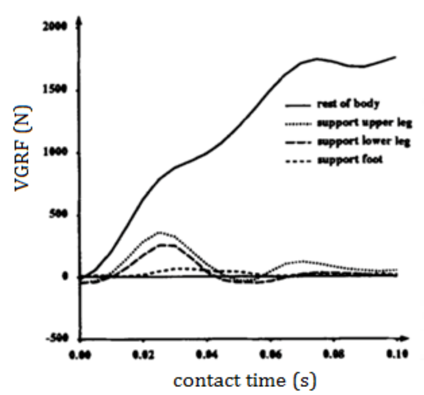

***Figure 8**:Adopted from Bobbert et al.* (7)*: Segmental contributions to VGRF.*

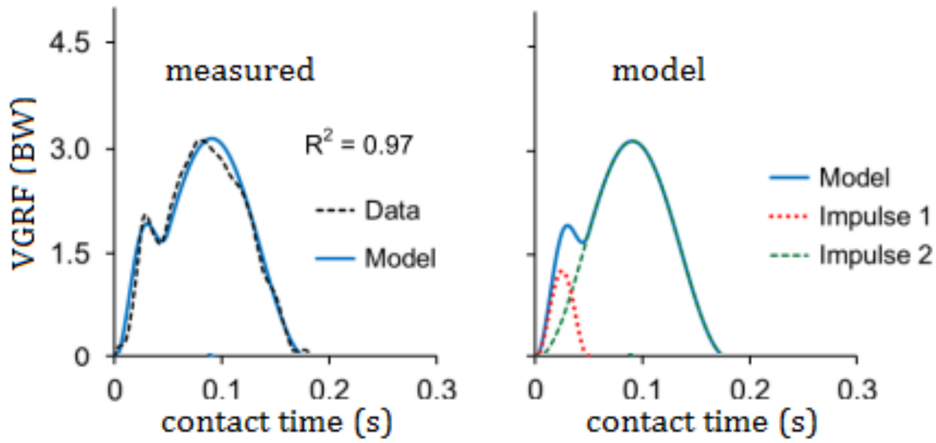

Figure 9*: Adopted from Clark et al.* (20)*: Modeled and actual VGRF. Impulse 1 represent the deceleration of the distal mass (8%) and Impulse 2 the deceleration of the rest of the body (92%).*

At initial foot contact, the position of the center of pressure is anterior to the body center of mass. This causes a horizontal braking force during the first half of stance slightly decelerating the body. After midstance, when the body center of mass passes the center of pressure, a horizontal propulsive force is generated accelerating the body. When running at a steady-state pace the horizontal decelerating 'braking' impulse and the accelerating 'propulsive' impulse have the same magnitude. In accelerating sprint running the propulsive impulse is larger than the braking impulse. The horizontal GRFs are much smaller in amplitude when compared to the VGRF. The medio-lateral GRF has been associated with frontal plane motions of the foot and ankle (78) and intrinsic and functional factors such as medial longitudinal arch of the runner's foot and the transverse plane angle between rearfoot and forefoot (41). However the relationship between medio-lateral GRF and running kinematics is less clear than for the other GRF components, due to the relatively small magnitudes of the medio-lateral GRF and the lack of a consistent pattern, which has been attributed to a great inter-subject variability. Fig. 10 shows example anterior-posterior and medio-lateral GRF-curves of runners with different running styles.

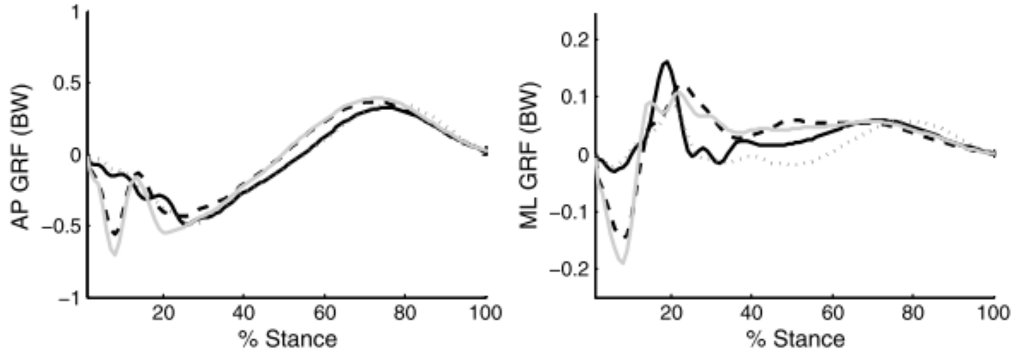

***Figure 10**: Adopted from Boyer et al.* (9)*: Anterior-posterior (left) (AP) and medio-lateral (right)(ML) example curves from runners with different running styles.*

3. INITIAL FOOT CONTACT PATTERN AS A MEASURE OF RUNNING STYLE

3.1. Different initial foot contact patterns

The most common way to classify running style is by describing the initial foot contact pattern which is based on the foot related initial contact point with the ground. Runners can be classified as an initial rearfoot (IRFC), midfoot (IMFC) or forefoot (IFFC) contact pattern (14)(fig. 11). Other separations with only two groups such as heel strike and non-heel strike are also possible. The rationale behind this approach is that the point of initial foot contact reflects the foot position at initial contact and as such influences the consecutive foot and ankle motion during stance.

***Figure 11**: Adopted from Larson et al.* (64)*: Examples of A. an initial forefoot (IFFC), B. and initial midfoot (IMFC) and C. an initial rearfoot contact pattern (IRFC).*

With an IRFC the runner makes initial contact with the ground with the posterior lateral aspect of the heel. Following an IRFC the ankle-foot complex shows an initial ankle plantar flexion. In an IFFC initial contact is made near the metatarsal-phalangeal joints while in an IMFC both anterior and posterior parts of the foot make contact at nearly the same time. Following an IMFC or IFFC the ankle shows an initial dorsiflexion (62, 90). In general, the currently available research suggests that when running shod at distance running preferred velocities about 75% of runners show an IRFC, about 20% an IMFC and 5% an IFFC (14, 50, 58, 60, 64).

3.2. Determination of IFCP

3.2.1. Strike Index (SI)

The most commonly used method to determine IFCP has been introduced by Cavanagh and Lafortune (14). A strike index (SI) is calculated based on the position of the center of pressure (COP) on the foot at initial contact and categorized by dividing the foot length into three equal parts (fig. 12). The SI is then expressed as a percentage of total foot length. An IRFC is defined with a SI from 0-33%, an IMFC with a SI between 33 and 66% and an IFFC with a SI >66%. This method uses force plate data and kinematic data to locate the COP along the length of the foot. COP measurements using only force plate data is less accurate when only low GRFs are exerted (8, 96) and this is the case at the instant of initial contact (appendix 3). Williams and Cavanagh (103) dealt with this issue by defining a SI at the instant when the vertical GRF reaches 10% of maximal vertical force, where already a certain amount of loading acts upon the foot. However, this adapted SI calculation has the disadvantage that SI is not assessed at initial foot contact, but shortly after it, while the initial segmental movements, building up the GRF and associated impact intensity are situated during this earliest phase of foot contact immediately following initial foot contact. In this thesis we will investigate the relationship between IFCP and impact intensity so we aim for a reliable SI for IFCP determination based on the very initial foot contact.

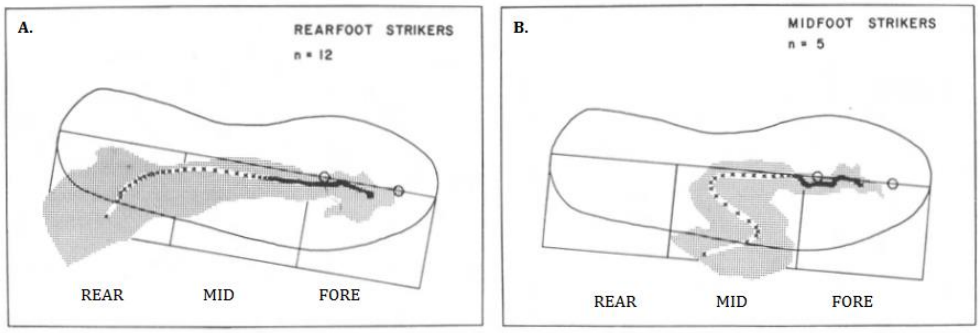

Figure 12*:Adopted from Cavanagh and Lafortune* (14)*: Mean COP locations under the shoe outline during foot contact. The shoe is divided into three equal regions for the purpose of classifying runners. The initial COP point is used to determine SI. A. Rearfoot strikers have tan initial COP position in the rear 1/3 and B. midfoot strikes have an initial COP position in the middle 1/3of foot length.*

To overcome the methodological difficulties of determining reliable COP data with low GRFs (appendix 3), a good alternative would be to use a high speed pressure plate system that also allows a direct localization of the COP on the foot sole (appendix 5) (24). The main advantage of such a system is the good spatial and temporal resolution even at low GRFs. Such a measuring system, e.g. the 2 m FootScan pressure plate made by RsScan, consists of small resistive sensors (0.5088 x 0.762 cm) (~spatial resolution), with a low measurement threshold (0.27 N/cm²) and is capable of high measurement frequencies (up to 500 Hz)(~temporal resolution). This should allow a more reliable COP determination at low GRFs which is the case at initial contact and immediately after, which would be the main improvement compared to COP calculations with only force plate. Moreover, a combined system using both a pressure plate and a force plate installed underneath would allow a dynamical calibration of the recorded pressures with the measured VGRF. This would partially counter the possible limitations in linear scaling that arise when using resistive sensors. As such, the summation of the measured pressures with the pressure plate will be matched to the measured VGRFs with the force plate underneath.

<u>RESEARCH QUESTION</u>

Q1. How can we more accurately assess strike index at initial foot contact during constant pace shod running?

H1. Using a combined high frequent plantar pressure and force plate system would result in reliable IFCP determination.

3.2.2. Visual

In field studies, e.g. during road racing events, IFCP has often been determined with a visual assessment based on high speed video images (50, 64) (fig. 11). An IRFC is defined when the heel or rear one-third of the foot touches the ground first, while in an IMFC the heel and the ball of the foot touch the ground nearly at the same time and in an IFFC the ball or front one-third of the foot touches the ground first. This method allows quick screening of large groups of runners, even in competition. However, initial foot inversion-eversion, adduction-abduction, low image resolution and inadequate measuring frequency sometimes make it hard to define the exact instant and location of initial contact which makes it especially hard to distinguish an IMFC from an IRFC or IFFC pattern (64).

3.2.3. Foot-to-ground angle

The kinematic determination of IFCP has been refined by Altman and Davis (1). Using a 3D high speed kinematic (Vicon, Oxford, UK) and kinetic (Bertec force plate, Columbus, OH, USA) measurement system, the authors determined the foot segment angle at initial contact and the SI. They hypothesized that SI could be estimated based on the foot-to-ground angle at initial contact when force data to calculate initial COP position and as such SI are not available. As they found a significant correlation between foot-to-ground angle and SI they concluded that foot-to-ground angle is an acceptable measure to determine IFCP when force data are not available. Based on the dataset from ten male and ten female runners the authors defined clear quantitative cutoffs: a rearfoot strike was determined at a foot-to-ground angle of 8.0° or more posterior inclination, a midfoot strike at a foot-to ground-angle between -1.6° anterior inclination and 8.0° posterior inclination and a forefoot strike at a foot-to-ground angle of -1.6° or less anterior inclination.

However, other more arbitrary cutoffs such as foot segment angles >0° or <0° to indicate a heel strike or a non-heel strike may also be used. This refined kinematic method provides a more continuous measure of the IFCP than a pure qualitative visual assessment and can be applied with the use of high speed video or more accurate motion capture systems. A possible limitation of this method is that without the use of force plate data it might be hard to determine the exact instant of initial foot contact. Also, when applying this method, based on 2D sagittal plane video data instead of force plate data the same limitations arise as with the visual determination method.

3.2.4. More complex measures

Some researchers suggested that incorporating measures of the actual foot-ankle kinematics or kinetics following initial foot contact could enhance the functional meaning of classifying IFCPs, although they have been less applied. Liebl *et al.* (68) described a rather complex clusteranalytical approach based on the ankle joint moment during the first 20% of foot contact. This method resulted in two clusters, well interpretable as rearfoot (~IRFC) and forefoot (~IFFC) footfall patterns. The general pattern of the ankle joint moment during the first 20% of foot contact of the rearfoot footfall group was characterized by an external ankle plantar flexion moment until about 15% of foot contact. The forefoot footfall group showed an external ankle dorsiflexion moment immediately following initial foot contact (fig. 13).

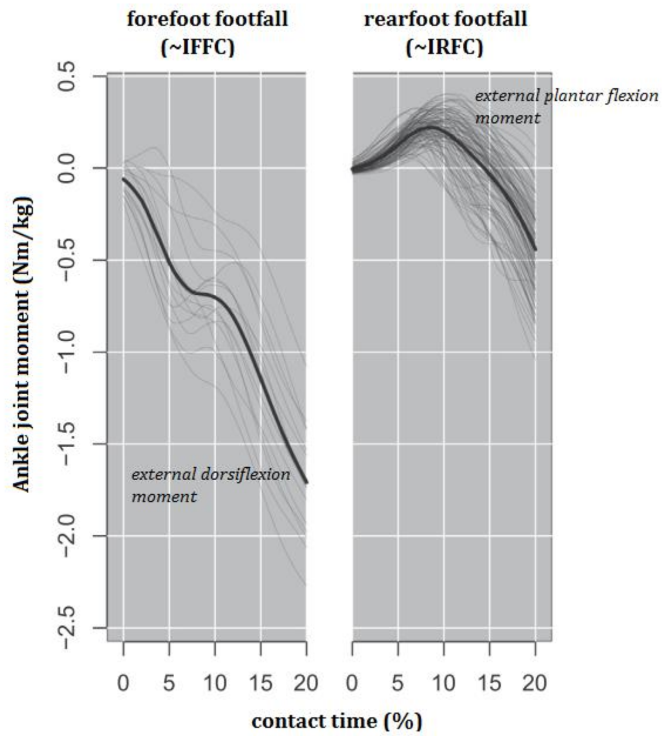

***Figure 13**: Adopted from Liebl et al.* (68)*: Ankle joint moment curves of the forefoot footfall (left) and rearfoot footfall (right) groups. These groups were constructed based on the ankle joint moment during the first 20% of contact time. Subjects were 119 male and female shod runners running at 3.5 m·s^{-1}.*

3.3. Influence of speed on IFCP

A study by Nigg *et al.* (79) about shod heel-toe running reported that when running speed increases from 3 to 6 m·s^{-1} the shank and rearfoot are more anteriorly tilted immediately before contact and that a flatter foot position is obtained at the highest running speed. These findings suggest that a subject's SI will increase at faster running speeds. This assumption is supported by a study by Keller *et al.* (58) that investigated the IFCP group distribution in a wide range of running speeds from 1-7 m·s^{-1}. IFCP group distribution changed from predominantly IRFC at running speeds below 5 m·s^{-1} to predominantly IMFC at speeds above 5 m·s^{-1} (fig. 14). Analysis of the SI indicated that the majority of subjects were rearfoot strikers at speeds less than 5 m·s^{-1} (fig. 14). At speeds above 3 m·s^{-1} there was an increasing frequency of midfoot and forefoot strikes. Eighty-six percent of the subjects were midfoot or forefoot strikers at 6.0 m·s^{-1}. These findings were confirmed by a study that assessed IFCP during marathon and half marathon racing events in elite distance runners that found a greater percentage of IMFC and IFFC in the faster runners (50). This shows that running speed may influence IFCP. However, Keller *et al.* did not report within-subject IFCP alterations due to a changed running speed (58). Moreover, not all subjects were able to complete the faster running trials. All males achieved speeds of 6 $m \cdot s^{-1}$ and four completed four or more trials at 7 $m \cdot s^{-1}$. Eight females achieved speeds of 5 $m \cdot s^{-1}$ and two completed five trials at 6 $m \cdot s^{-1}$. As such, maybe only the faster runners (that maybe already are more likely to use an IFFC) remained at the higher running speeds which may have given a distorted view of the IFCP distribution at the higher running speeds. Assessing intra-individual alterations in SI, determined with a sensitive pressure plate, should provide a better insight in the relationship between running speed and SI.

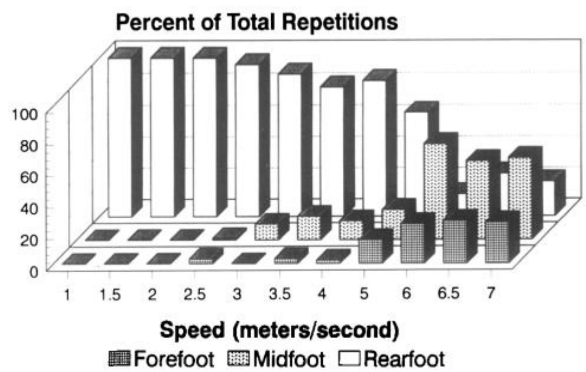

***Figure 14**: Adopted from Keller et al.* (58)*: Initial foot contact patterns (rearfoot, midfoot, forefoot) versus speed. Subjects were 23 recreational athletes.*

The observed interaction between IFCP and speed, but the lack of information about the intra-individual alteration in SI due to an increase in speed leads to the following research question of this thesis:

RESEARCH QUESTION

Q2. What is the within-subject effect of running speed on IFCP?

H2. Most runners show an IRFC but with increasing velocity some of these runners make a shift towards an IMFC or IFFC.

3.4. Other influencing factors

Apart from running speed, also the shoe or contact surface can influence running biomechanics and in some extreme cases might even change ones IFCP (15–17, 40, 73, 79, 80, 89). A study by Lieberman *et al.* (66) even states that the elevated and cushioned heel of the modern running shoe facilitated IRFC while IFFC actually is the 'natural' IFCP, based on the high prevalence of IFFC in habitually barefoot runners. The elevated heel in standard running shoes might limit the lowering of the heel as a mechanism of initial ankle dorsiflexion in an IFFC, and ankle dorsiflexion is more likely to be achieved by the tibia passing over the foot. Also with shoes with elevated heels, a similar foot position results in a more posteriorly inclined sole angle compared to barefoot running, and as such facilitates an IRFC.

Shoe design and especially heel-toe offset have been shown to influence IFCP. Chambon *et al.* (15) have tested runners at 3.0 $m \cdot s^{-1}$ on a track, wearing shoes with a varying heel-toe offset ranging from zero drop (D0) to an 8 mm drop (D8) and running barefoot. The authors found a higher foot-to-ground angle and smaller SI in the D8 condition compared to the D0 condition, which indicates that a shoe with a more pronounced heel-toe offset indeed resulted in a more pronounced IRFC.

Not only shoe characteristics, but also the absence of shoes has been shown to influence running kinematics. Most habitual shod runners change their running style when running barefoot and show a less dorsiflexed ankle and less posteriorly inclined foot-to-ground angle at initial foot contact (4, 16, 49, 105) and a more flexed knee joint with a lower knee joint flexion range of motion during stance (16, 43, 105). These alterations lead to an IMFC or IFFC when running barefoot compared to mostly IRFC when running shod. The alteration from an IRFC to an IMFC or IFFC has been attributed to the lower impact transient peak of the VGRF in IMFC or IFFC. Also by adopting a 'flatter' foot position runners limit the local peak pressures at the heel (105). The relationship between IFCP and impact intensity will be described further in this introduction ('6.2. IFCP and impact intensity'). Gruber *et al.* (48) found that when habitual rearfoot strikers ran barefoot on a soft surface, not all runners changed their IFCP, indicating it is not just the presence or absence of a shoe but also the contact surface properties that influence the chosen IFCP. In this thesis we will not further elaborate on the barefoot-shod comparison, or the rising of the minimal shoe trend which is a current ‘hot topic’ in running biomechanics, since the vast majority of runners still runs with conventional standard running shoes. For the interested reader, we refer to a review on barefoot running by Hsu (56) or Lieberman (67) and a description of the biomechanical characteristics of barefoot footstrike modalities by Nunns *et al.* (85).

If researchers wanted to assess IFCP and intrinsic running technique differences, not confounded by differences in footwear but in realistic shod conditions, subjects should run in a neutral type shoe. This was not the case in the road race studies (50, 60, 64) in which subjects wore their own running shoes which could have influenced IFCP differences between subjects.

4. IMPACT IN RUNNING

4.1. Impact parameters in running

4.1.1. Vertical transient impact peak

The most representative measure for impact intensity is the temporal progress of the VGRF. As follows, most measures for impact intensity are derived from the temporal VGRF progress. The initial transient impact peak in VGRF is commonly associated with the impact of the foot striking the ground in IRFC. This peak occurs within the first 0.050s of foot contact (83). The second peak is caused by the slower (compared to the stance leg) deceleration of the rest of the body (7, 29). The magnitude of the transient impact peak has often been used to quantify the impact intensity during heel-toe running (fig. 7). In initial mid- or forefoot contact patterns this initial transient impact peak is often absent. Moreover, as previously stated (2.4. Ground reaction forces in distance running) this variable might not be the best parameter to assess impact intensity. Shorten *et al.* (95) looked at the spatial distribution of the vertical GRF (VGRF) in runners with an IRFC. The VGRF was subdivided in force acting upon the rearfoot and upon the distal parts of the foot (mid- and forefoot). The VGRF was not only divided into spatial components, but also into frequency components. Such analysis allows to separate the impact characteristics (~high frequencies) and the rest of the curve (~low frequencies)(29). The GRF was divided into high frequency components (>10Hz) associated with the impact and low frequency components (<10 Hz). The authors found that low frequent VGRF components originating from both the heel and distal parts of the foot contributed about half of the magnitude of the 'heel' 'impact' peak. This finding supports the title of the study that the 'heel impact' peak is neither heel nor impact. These findings might explain the inconsistent research findings regarding the effect of shoe cushioning (mainly at the heel part of the shoe) and the inconsistency between in vitro and in vivo testing on the magnitude of the transient impact peak (21, 57, 69, 79, 81, 86, 106). In other words, when assessing impact intensity, using the magnitude of the transient impact peak might be ill-advised, as its amplitude is not only influenced by the high frequent impact-like deceleration of the distal masses but also by the non-impact like low frequent deceleration of the 'rest of the body'. However, it is still a part of the GRF and therefore it acts on the biological system as a whole.

The VGRF can be decomposed into the contribution of the stance leg decelerations and the contribution of the deceleration of the rest of the body. Analogues to this decomposition a spectral decomposition can be performed, decomposing the VGRF into a low frequency component (~non-impact, ~rest of body deceleration) and a high frequency component (~impact, ~distal mass deceleration). Shorten *et al.* (95) used a 10 Hz cutoff frequency to distinguish high and low frequency VGRF signal content. Such analysis allows to separate the impact characteristics from the rest of the VGRF curve. As such, the magnitude of the peak of the high frequency component can be regarded as a measure for the impact intensity and can also be calculated for IMFC of IFFC when there is no transient impact peak in the VGRF curve. Figure 15 shows an example of such a spectral decomposition of the VGRF.

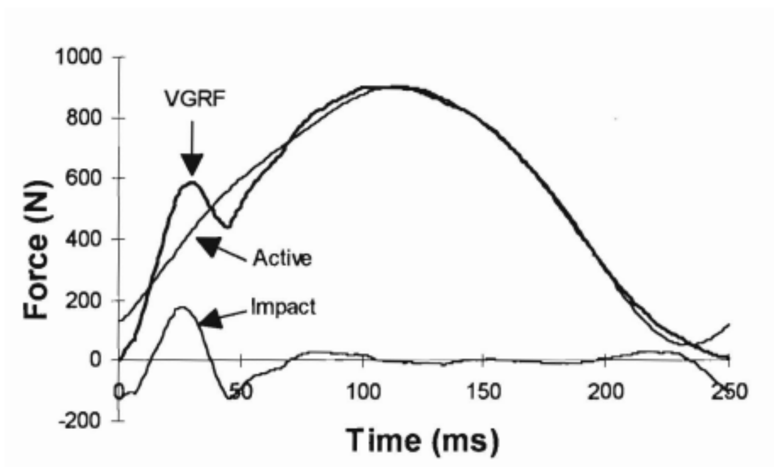

***Figure 15**: Adopted from Derrick et al.* (29)*:Example of the spectral decomposition of the VGRF into an active (~low frequency) and impact (~high frequency) component.*

4.1.2. Loading rate

Another measure for impact intensity is the loading rate of the VGRF. This measure has also been associated with a history of stress fractures (76, 108) explaining the relevance and frequent use of this measure. The loading rate can be calculated as average loading rate of the VGRF (VALR) (between certain GRF thresholds) or as peak instantaneous loading rate of the VGRF

(VILR) (fig. 16). In other words these values represent the steepness of the slope of the VGRF during the initial impact phase. In this thesis we defined the initial impact phase as the first 0.050 s of foot contact. This timeframe was based on the fact that impact forces in running reach their peak earlier than 0.050 s after initial contact (83, 95) . Moreover, Shorten *et al.* (95) defined high frequency signal components with frequencies above 10 Hz as impact signals, that as such show a half oscillation time of 0.050 s or shorter.

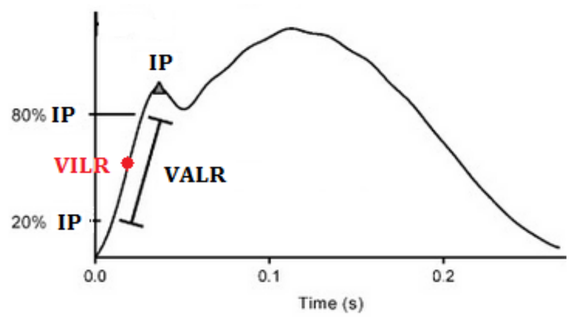

***Figure 16**: Adopted from Samaan* (94)*: Example VGRF curve with indication of VILR and VALR*

Due to its relationship with a retrospective occurrence of stress fractures and its direct relation with the progress of the VGRF during the initial impact phase, in this thesis we used VILR as a main variable to assess impact intensity. In the third study of this thesis both VILR and the peak of the high frequency component of the VGRF were used as impact intensity measures. Although the relation between retrospective tibial stress fractures has been shown for both VILR and VALR, we chose to use VILR as a main dependent variable in the first and second study in this thesis. VILR is calculated as the peak value of the first derivative of the vertical GRF during the initial impact phase. The calculation of VALR is less straight-forward and is calculated over a certain time interval. Mostly this parameter has been calculated in IRFC running (76, 91, 109) and determined over different time intervals: from initial contact until the 'initial' impact peak, from a 200N threshold to 90% of the initial 'impact' peak, from 20 to 80% of the initial impact peak, … This approach is problematic when the initial transient impact peak is absent. In these cases VALR has been calculated from a 200N threshold to 6% of contact time (66). In the studies in this thesis we only calculated VILR as this variable can be easily and similarly determined for the different IFCPs.

4.1.3. Peak tibial acceleration

Another impact intensity measure, indirectly associated with the VGRF progress is the peak tibial acceleration, defined as the maximal positive acceleration measured with a lightweight accelerometer firmly attached to the distal part of the tibia. Also this peak tibial acceleration has proven a relevant variable as it is found to be higher in runners with a stress fracture history (55, 76). However, some researchers found no difference in peak tibial acceleration between stress fracture and non-stress fracture groups (108, 110). The peak tibial accelerations has been found to be significantly correlated with the average and instantaneous loading rates of the VGRF (52, 53, 65) and moderate correlated with the magnitude of the transient impact peak (52). Figure 17 shows an example curve of a tibial acceleration signal and the VGRF. Moreover, the peak tibial acceleration has proven a successful measure in gait retraining studies using biofeedback to reduce impact intensity in running (19, 26, 27).

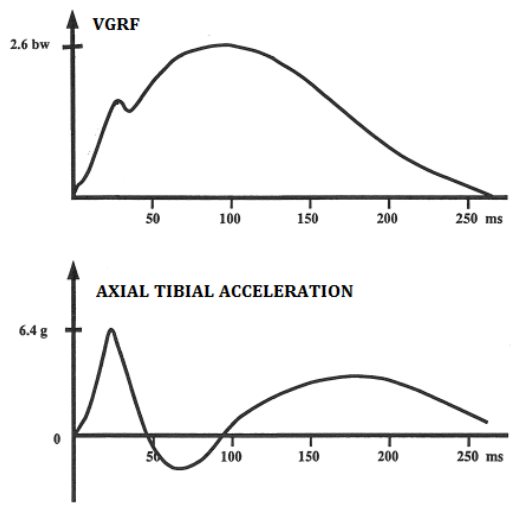

***Figure 17**: Adopted from Hennig et al.* (53)*: Typical VGRF (BW) and axial tibial acceleration (g) with a peak tibial acceleration of 6.4g (along the longitudinal axis of the tibia) during the stance phase of running at 3.3* $m{\cdot}s^{-1}$.

4.2. Etiology of the impact

The GRF signal is composed of the superimposition of the mass-acceleration products of all body segments while contacting the ground. Bobbert *et al.* (6, 7) recomposed the VGRF by calculating the contribution of each segment to the VGRF with an eight-segment kinematic model. Clark *et al.* (20) used a modelling approach in which the VGRF was modelled as the impulses generated by the deceleration of a distal mass and a 'rest of body' mass. Both studies showed that the VGRF during the initial impact phase represents the deceleration of both distal masses and the rest of the body. As such, all factors that influence distal and/or total body decelerations also influence impact intensity.

In their study, Bobbert *et al.* (7) constructed the kinematic model based on visual marker positions from high speed video data (200 Hz) from three cameras, processed with Expert vision 3D software. Nowadays, more complex 3D measurement systems (e.g. opto-electronic motion capture systems) should allow to obtain more accurate segmental positional data. Analyzing the segmental decelerations and their contribution to VGRF would provide mechanical 'proof' of VGRF and impact intensity differences between runners with different running styles.

RESEARCH QUESTION

Q3. What are the differences in segmental contributions to the VGRF between runners with different IFCPs and how do they relate to differences in impact intensity?

H3. We hypothesize that the greater impact intensity in an IRFC can be explained by a greater contribution of the fast deceleration of distal segments when compared with an IMFC or an IFFC.

4.3. Factors influencing impact intensity

4.3.1. Running speed

In a study by Nigg *et al.* (79) fourteen male heel-toe runners ran at 4 speeds (3, 4, 5, 6 m·s^{-1}) while VGRFs were recorded. As measures for impact intensity the authors determined the magnitude and timing of the transient vertical impact peak and the magnitude and timing of the peak vertical loading rate. Both the magnitude of the impact and the loading rate were found to increase with increasing running speed. The impact peak and the maximal loading rate occurred earlier in the stance phase with increasing running speed (fig. 18). The mechanical explanation can be found in the increasing vertical touchdown velocity of the heel with increasing speed. However, the vertical touchdown velocities of the heel increased to a greater extent than the impact peak and loading rate. The authors also found that with increasing running speed the knee angle at touchdown became more flexed. This alteration in touchdown geometry could be seen as a 'protection' against the increased vertical touchdown velocity.

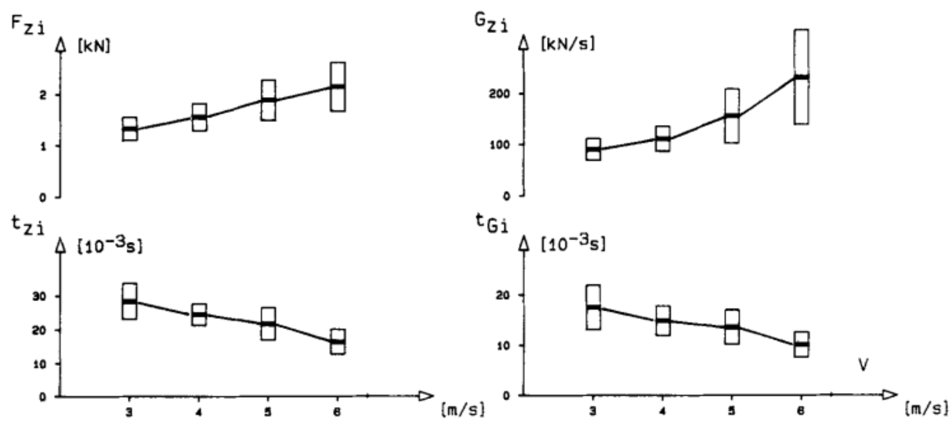

Figure 18: *Adopted from Nigg et al.* (79)*: Influence of running speed (v) on the transient vertical impact peak magnitude (F_{zi}) and timing (t_{zi}) and on peak vertical loading rate magnitude (G_{zi}) and timing (t_{Gi}).*

Apart from an increased touchdown velocity of the heel with increasing running speed, also contact times are known to decrease and flight times to increase with increasing running speed from 3 to 6 m·s^{-1} (101). This implies a faster deceleration of the total body mass as greater change in vertical velocity over a shorter time period is realized. As such, both the deceleration of distal masses and the total body could account for the increased impact intensity with increasing running speed as we know that the VGRF consist of the superimposition of both distal and 'rest of body' contributions.

4.3.2. Interface between foot and ground: footwear

A multitude of studies has focused on the influence of footwear characteristics on the impact intensity of running. Many contradictions have arisen from these studies that most frequently assessed the impact peak magnitude as measure for the impact intensity when running in shoes with varying midsole cushioning properties. Most *in vitro* mechanical tests of running shoe properties confirmed that under constant impact conditions, more compliant sole materials result in a longer time to peak, lower peak force, lower loading rate and greater deformation of the cushioning system (95). However, *in vivo* studies showed less uniform findings. Some studies have found a decrease in impact peak magnitude with more compliant shoe soles (69, 86) while others found no effect of shoe conditions (21, 51, 57). Some studies even found an increase in peak forces with more compliant shoes (79, 106). A possible explanation for these contradicting research findings has been given by Shorten *et al.* (95) who have shown that the 'heel' 'impact peak' during heel-toe running consists of both low frequent (~non-impact) and high frequent signals and of both VGRF contributions from proximal (~heel) and distal parts of the foot (~mid- and forefoot). As such, the mechanical properties of a cushioning shoe heel part might not always be reflected in the magnitude of the impact peak. In this thesis the influence of footwear on the impact intensity in running was not retained as one of the research purposes. Being aware of the possible influence of footwear, subjects all wore the same neutral running shoe (Li Ning Magne) during the running tests that were taken.

Not only footwear characteristics, but also the absence of footwear is known to influence the running kinematics and impact intensity (105). A much-discussed paper by Lieberman *et al.* (66) that was published in Nature showed that experienced barefoot runners were characterized by lower impact intensities because they ran with an IFFC. Since the publication of that paper lots of research has focused on the shod-barefoot comparison in running. In this thesis, this aspect was not investigated.

4.4. Relation between running kinematics and impact

It is clear that running kinematics influence the impact intensity during each running step. In table 1 we provide an overview of which kinematic parameters/characteristics have been related to impact intensity. Since mainly VILR has been related to an increased stress fracture injury susceptibility (76, 108), we will focus on kinematic parameters related to VILR. However, both peak tibial acceleration and the transient impact peak magnitude have been shown to be correlated with VILR (65). In the second study of this thesis we performed a kinematic comparison of the different IFCPs with an emphasis on impact related kinematics. The most logical differences would be related to the distal ankle and foot kinematics that are known to be related to impact severity as the classification of different IFCPs is based on the foot positioning at initial foot contact. In IRFC the posteriorly inclined foot position and ankle dorsiflexion position at initial foot contact allow for an initial ankle plantar flexion (45). Together with the deformation of the cushioned rear section of the shoe midsole and the fat pad of the heel these are regarded as impact reducing ‘strategies’ or mechanisms in a typical IRFC (22, 105, 107). These mechanisms are not (or less) possible in IMFC and IFFC running due to the ‘flatter’ initial foot positioning. In IMFC and IFFC an initial ankle dorsiflexion motion is regarded as a principal impact reducing strategy (19, 66, 89). Also the initial pronation following initial foot contact has been regarded as an impact reducing mechanism in IRFC running (93). However, so far no study has assessed the kinematic differences between different habitual IFCPs in an inter-subject design and their relation with impact intensity.

***Table 1**: Kinematic parameters associated with impact intensity.*

Kinematic parameter	Relation with impact intensity	Study
IFCP	VILR IRFC > VILR IMFC or IFFC	(9, 46, 62, 66)
Stride length	Increased stride length ~ increased VILR	(54)
Stride frequency	Decreased stride frequency ~ increased VILR	(54)
Knee flexion at initial contact	increased knee flexion ~ decreased peak impact forces and peak leg deceleration	(31, 63)
Knee flexion range of motion	increased knee flexion range of motion ~ decreased peak tibial acceleration	(77)
In IRFC running: sagittal plane foot-to-ground angle	decreased foot to ground angle ~ increased VILR	(45) (model simulation study)
Heel vertical touchdown velocity	Increased heel vertical touchdown velocity ~ increased VILR	(45) (model simulation study)
Shank angle at initial contact	More vertical shank angle at initial contact ~increased peak tibial acceleration	(77)
Ankle dorsiflexion	An increase in ankle dorsiflexion at initial contact ~ decrease in VILR and peak tibial acceleration	(19)

RESEARCH QUESTION

Q4. What are the kinematic differences between the inter-individually different IFCPs?

H4. Main kinematic differences are situated at the distal ankle and foot kinematics.

4.5. Muscle action and impact

Since muscles control the movement of joints and segments, it is obvious that muscle actions are able to influence the impact of running with active mechanisms. Such active mechanisms include changes in segment geometry, adjusting joint stiffness, eccentric muscle contractions or increased muscle (pre)activation (7, 30, 45, 71, 92). As muscle latency is 0.035-0.075 s, muscles may not be able to respond to impact forces as they occur (97). However, a pre-activation of muscles before initial contact might be an anticipatory strategy to influence the following impact (10, 45, 100).

The influence of altered segment orientations, caused by muscle activation, is through influencing the possibility for joints to absorb energy with eccentric muscle contraction and by influencing the effect that a change in joint angle has on the lowering of the body(segments). The movement that occurs at each joint is partially determined by the joint stiffness. Theoretically, if all other conditions remain the same, an increased joint stiffness should result in increased impact forces.(82)

Muscles can absorb energy by eccentric contraction that controls the deceleration of the body (30). By prolonging the time during which the body or separate segments are decelerated, impact intensity can be limited. In running with an IRFC, eccentric contractions of the tibialis anterior, tibialis posterior and flexor hallucis longus muscles control ankle pronation and initial plantar flexion and as such the lowering of the forefoot to the ground (45, 84). In running with an IFFC, eccentric contractions of plantar flexor muscles absorbs energy and controls the lowering of the heel and the rest of the body to the ground (93). Differences in the combination of initial ankle eversion, pronation, dorsi- or plantar flexion might be related to the differences in impact loading characteristics between the different IFCPs (65).

The human body is not a chain of rigid segments. The skeletal system is fairly rigid, but the biological systems surrounding it (e.g.: muscles, skin, internal organs, adipose tissue, …) are not. When impacting the ground during running, the rapid deceleration of the skeletal structures cause high impacts. However, the non-rigid structures surrounding the skeleton can move relatively to it and are not decelerated as fast as the skeletal structures. The slower deceleration of these non-rigid structures can limit the impact forces. An increased muscle activity in both lower and upper extremities is believed to increase the overall rigidity of the system and consequently the impact forces (82).

5. RELEVANCE OF DISTINGUISHING DIFFERENT INITIAL FOOT CONTACT PATTERNS

5.1. IFCP and running economy and performance

In elite distance runners, a greater proportion use an IFFC or IMFC than in recreational runners (50, 60). This has led to the belief that there are performance benefits when running with an IFFC or IMFC. Moreover, it has been hypothesized that in IFFC a lower metabolic cost is reached because of a more efficient storage and release of elastic energy in the plantar flexor muscles (Achilles tendon) (3, 50, 89). However, a recent study by Ogueta-Alday *et al.* (87) with ten habitual IRFC and ten habitual IMFC sub elite runners found that habitual IRFC runners are more economical than IMFC runners at submaximal running speeds (11-15 $km \cdot h^{-1}$) and showed longer contact times and shorter flight times. No significant differences in stride frequency and stride length were found. This shows that the hypothesis about IFFC or IMFC being more metabolically efficient might not be true.

5.2. IFCP and impact intensity

The classification of IFCPs might be more relevant to relate with the intensity of the GRF during the initial impact phase than to relate with running economy. During each running foot contact, the foot strikes the ground resulting in a rapid rise of the GRF. The most uncomplicated mechanical model, a spring-mass model (72) ('3.1. Biomechanical simulation models') predicts the resulting GRF from a running step as a sinusoidal pulse with a peak magnitude of 2 to 3 times bodyweight (BW). As already mentioned, most runners show a running style in which initial foot contact is made with the rearfoot. In such IRFC the GRF shows an additional initial transient 'impact' peak which is much smaller or even absent in IMFC of IFFC (fig. 19). This has led to the belief that running with an IRFC induces the greatest impact intensity and as such might evoke a higher stress fracture injury susceptibility. The vertical loading rate of the GRF, a commonly used variable to assess impact intensity ('4.1. Impact parameters in running'), has been shown to be lower in IFFC or IMFC when compared with IRFC (18, 33, 46, 47).

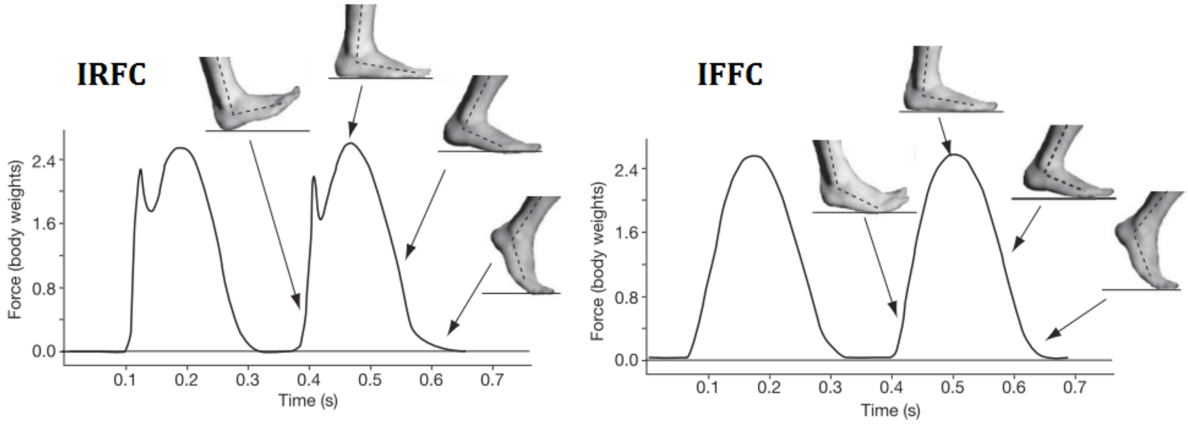

***Figure 19**: Adopted from Lieberman et al.* (66)*: Example GRF from running with an IRFC (left) and an IFFC (right).*

However, recent research by Boyer *et al.* (9) with fifteen habitual IFFC/IMFC and fifteen habitual IRFC runners found that when runners ran with their habitual IFCP the peak resultant loading rate of the GRF was similar and the peak vertical instantaneous loading rate of the GRF (VILR) were only slightly lower in habitual IFFC. Laughton *et al.* (65) also did not find a significant difference in VILR between IFFC and IRFC.

It is clear that the initial foot positioning in the different IFCPs should influence the consecutive mass deceleration, and as such the temporal progress of VGRF, during the initial impact phase and as such the impact intensity. A study comparing running kinematics and impact intensity between runners with different habitual IFCPs (inter-subject approach) could assess the kinematic differences between these patterns and the link between the kinematic differences and possible differences in impact intensity. In the studies in this thesis we compared IFCPs with an inter-subject design, because we wanted to assess differences between habitual IFCPs and not the effect of changing IFCP. The advantage of such an approach is that runners run with their habitual IFCP. A disadvantage is that the relationship between running kinematics and impact intensity are not directly causal. That is, the intra-subject effect of changing running kinematics on impact intensity cannot be assessed.

As IFCP influences the consecutive foot and ankle motion (90) and is related to impact intensity (9, 11) we hypothesize that IFCP will be related to the spatial distribution of the VGRF impact intensity over different foot zones (e.g. rear-, mid- and forefoot). Assessing the spatial distribution of the impact intensity could allow to identify, for different IFCPs, which foot zones experience the highest 'impact loading' and could provide useful indications for possible instructions on passive cushioning in running footwear, specific for different IFCPs.

RESEARCH QUESTION

Q5. What is the difference in impact intensity, as measured with VILR, between the different IFCP types?

H5. Subjects with an IRFC show higher VILRs than subjects with an IMFC or IFFC.

RESEARCH QUESTION

Q6. What is the relationship between the observed kinematic differences (Q4.) between the different IFCPs and the impact severity, as measured with VILR.

H6a. We hypothesize that mainly distal kinematic parameters will correlate with VILR

H6b. We hypothesize that for IRFC different kinematic characteristics (e.g. initial ankle plantar flexion) will be correlated with VILR than for IMFC (e.g. initial ankle dorsiflexion) given their different initial ankle and foot movements.

RESEARCH QUESTION

Q7. Does the spatial distribution of the VGRF impact intensity over different foot zones differ in runners with different IFCPs?

H7. We hypothesize that runners with an IRFC will have the greatest impact intensity under the rearfoot, whereas runners with an IMFC or IFFC will have the greatest impact intensity under the mid- or forefoot zone.

5.3. Impact as a risk factor for injuries

The relevance of discerning different IFCP can be found in their possible relationship with impact intensity and the related injury susceptibility. Stress fractures are a type of overuse injuries caused by repetitive muscle forces together with bending and impact forces acting on the bone, which has not adapted to the loading (88). Stress fractures at the lower-limb are one of the most common injuries sustained in runners (13, 76, 98) and represent up to 20% of all sport injuries (98). The distal tibia and the metatarsal head are the most frequently affected sites (13). An optimal amount of impact is suitable to develop and maintain bone tissue health without causing overuse injuries (42). However, the repetitive impact shocks during each running foot contact have been reported as a primary mechanical cause of stress fractures (32).

Several studies have hypothesized, that the loading rate of the VGRF influences stress fracture development (28, 76, 108). Moreover, runners with a history of stress fracture injury have been found to exhibit higher loading rates and peak tibial accelerations when compared with non-injured runners (55). In a preliminary, prospective study Davis *et al.* (28) reported higher peak tibial accelerations and VGRF loading rates (both average and instantaneous) in a group of runners that developed tibial stress reactions compared to a control group. Also other, less frequently used parameters such as free moment (75) and angle of the GRF in the frontal plane (25) have been associated with the occurrence of tibial stress fractures. However, few prospective studies have been able to determine the biomechanical risk factors of tibial stress fractures. The direct relation between high external loading rates and stress fractures is not that absolutely verified. Prospective studies need to determine possible risk factors and aim at understanding the underlying mechanisms.

A primary target of gait retraining studies has been to reduce the impact intensity in running (19, 26, 27, 46). Based on the absence of a transient impact peak in the VGRF and lower VGRF loading rates of runners with an IFFC or IMFC, some of these gait retraining studies have even instructed runners on adopting an IMFC to reduce the impact intensity (46). However, a kinematic comparison of runners performing their habitual IFCP and the relationship between the (impact related) kinematic differences between the IFCPs is still needed. There is a need for a better understanding of the relationship between running impact intensity and (IFCP related) kinematics.

6. AIMS AND HYPOTHESES

The most common method to determine IFCP is the SI method developed by Cavanagh and Lafortune (14). This method uses force plate data to determine the COP position on the foot at initial foot contact. Since the COP determination with force plates is less accurate at low GRFs, which is the case at initial foot contact, this method could be optimized by using measuring systems that can more accurately determine COP at low GRFs. Moreover, the intra-individual relation between running speed and IFCP is still unknown. Therefore the first study in this thesis aims to accurately assess IFCP with an optimized SI determination method using both force plate and high frequent plantar pressure plate data. IFCP will be determined with this optimized method in a group of endurance runners when running shod at a range of endurance running velocities. As such the intra-individual relation between IFCP and speed will be assessed. We hypothesize that using a combined high frequent plantar pressure and force plate system would result in reliable IFCP determination. Also, we hypothesize that most runners show an IRFC but with increasing velocity some of these runners make a shift towards an IMFC or IFFC.

The earlier established idea that an IMFC or IFFC is characterized by a lower impact intensity when compared to an IRFC has recently been applied in gait retraining studies aiming at impact reduction. Also wearing ‘minimal’ footwear has been used to evoke an IMFC or IFFC. Therefore, we have to be sure of the relation between IFCP, determined with an optimized SI method, and impact intensity. As a consequence, a second aim of the first study is to assess the differences in impact intensity, as measured with VILR, between different IFCPs, determined with an optimized SI method, over a range of endurance running velocities. We hypothesize that subjects with an IRFC show higher VILRs than runners with an IMFC or IFFC.

If IFCP is indeed related to impact intensity, there must be some kinematic differences between the different IFCPs. As IFCP is related the initial foot position, there will be at least some distal ankle and foot kinematic differences between the different IFCPs. The second study in this thesis aims to assess the kinematic differences between different IFCPs. Also this study will assess the relation between these kinematic differences and the differences in impact intensity, as measured with VILR. In other words this study will assess the impact related kinematic differences between different IFCPs. We hypothesize that the main kinematic differences are situated at the distal ankle and foot kinematics. Also, we hypothesize that mainly distal kinematic parameters will correlate with VILR. We also hypothesize that for IRFC different kinematic characteristics (e.g. initial ankle plantar flexion) will be correlated with VILR than for IMFC (e.g. initial ankle dorsiflexion) given their different initial ankle and foot movements.

As IFCP influences the consecutive foot and ankle motion and is related to impact intensity we hypothesize that IFCP will also be related to the spatial distribution of the VGRF impact intensity over different foot zones (e.g. rear-, mid- and forefoot). Therefore, in the third study in this thesis we aim to assess the spatial distribution of the impact intensity which could allow to identify, for different IFCPs, which foot zones experience the highest 'impact loading'. Apart from VILR, also the magnitude of the high frequency components VGRF can be used to assess impact intensity. Such data could provide useful indications for possible instructions on passive cushioning in running footwear, specific for different IFCPs. We hypothesize that runners with an IRFC will have the greatest impact intensity under the rearfoot, whereas runners with an IMFC or IFFC will have the greatest impact intensity under the mid- or forefoot zone.

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STUDY 1

Relationship between running speed and initial foot contact patterns

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ABSTRACT

Purpose. This study assessed initial foot contact patterns (IFCP) in a large group of distance runners and the effect of speed on the IFCP. **Methods.** We determined the strike index, to classify the runners in IFCP groups, at 4 speeds (3.2, 4.1, 5.1, 6.2 $m \cdot s^{-1}$) by measuring center of pressure (COP) with a 2 m plantar pressure plate. Such a system allows a direct localization of the COP on the plantar footprint and has a low threshold value (2.7 $N \cdot cm^{-2}$) resulting in more accurate COP data at low ground reaction forces than when obtained from force plate. **Results.** The IFCP distribution evolves from mostly initial rearfoot contact (IRFC) (82%) at 3.2 $m \cdot s^{-1}$ to more anterior foot contacts with about equal distribution of IRFC (46%) and initial midfoot or forefoot contact (IMFC+IFFC) (54%) at 6.2 $m \cdot s^{-1}$. About 44% of the IRFC runners showed atypical COP patterns with fast anterior displacement of the COP along the lateral shoe margin. Apart from the different COP patterns, these atypical IRFC were also characterized by a significantly higher instantaneous vertical loading rate than the typical IRFC patterns. **Conclusion.** The IFCP distribution changes were due to intra-individual alterations in IFCP at higher speeds. That is, 45% of the runners made one or even two 'transitions' towards a more anterior IFCP (and 3% shows some other type of transition between initial foot contact styles as speed increases). Although, 52% of the runners remained with the same IFCP.

INTRODUCTION

In running, strike patterns may be classified into three groups based on the foot related initial contact point: an initial rearfoot (IRFC), midfoot (IMFC) or forefoot (IFFC) contact pattern (5). Other separations with only two groups such as heel strike and non-heel strike are also possible. The way the foot initially makes contact with the ground influences the consecutive foot motion during stance. Following an IRFC the ankle-foot complex shows an initial ankle plantar flexion while an IMFC and an IFFC is followed by an initial ankle dorsiflexion (37). It has also been shown that a habitual shod IRFC is characterized by higher loading, at least as defined by selected variables, when compared with a shod IFFC (39) or a shod IMFC (2,15), after habitual IRFC subjects were instructed to run with these altered strike patterns without changing the shoe conditions. This has led to, sometimes highly debated, hypotheses about associations between initial foot contact pattern (IFCP) and the etiology of injuries (9,11,26,31). The increased scientific interest for this topic raises the need for reliable methods for measuring IFCPs.

The two most commonly used methods for IFCP determination are a kinematic determination of IFCP and the calculation of a strike index (SI) that uses both kinetics and kinematics. In field studies, the **kinematic method** has mostly been applied with video images. An IRFC is defined when the heel or rear one-third of the foot touches the ground first, while in an IMFC the heel and the ball of the foot touch the ground nearly at the same time and in an IFFC the ball or front one-third of the foot touches the ground first and no heel contact is made (19). This method allows quick screening of large groups of runners, even in competition. However, initial foot inversion-eversion, adduction-abduction, low image resolution and inadequate measuring frequency sometimes make it hard to define the exact instant and location of initial contact. It is especially hard to distinguish an IMFC from an IRFC or IFFC pattern (25). Altman and Davis (1) refined this kinematic method by measuring the foot segment angle at initial contact. The authors defined clear quantitative cutoffs but others may use foot segment angles > 0° or < 0° to indicate a heel strike or a non-heel strike. This refined kinematic method provides a more continuous measure of the IFCP than a pure qualitative visual assessment and can be applied with the use of high speed video or motion capture systems.

Another frequently used method is the determination of a **SI** (5) which is based on the position of the center of pressure (COP) on the foot at initial contact. This method uses force plate data and kinematic data to locate the COP along the length of the foot. COP measurement using only force plate data is less accurate when only low ground reaction forces (GRF) are exerted (4) and this is the case at the instant of initial contact. Williams and Cavanagh (38) dealt with this issue by defining a SI at the instant when the vertical GRF reaches 10% of maximal vertical force, where already a certain amount of loading acts upon the foot. A good alternative would be to use a more sensitive high speed pressure plate system that also allows a direct localization of the COP on the foot sole (8).

Several studies have determined IFCP in a large number of distance runners both in 'competition' using the kinematic determination method (19,24,25) and in 'laboratory' conditions using the SI method (5,23) or the kinematic determination method (11). In general, the currently available research suggests that when running shod at submaximal running velocities about 75% of runners show an IRFC, about 20% an IMFC and 5% an IFFC (5,19,23,24,25). However, the reported IFCP group percentages results are influenced by the IFCP determination method, running speed and subject group characteristics.

A study by Nigg *et al.* (32) about shod heel-toe running reported that when running speed increases from 3 to 6 $m \cdot s^{-1}$ the shank and rearfoot are more anteriorly tilted immediately before contact and that a flatter foot position is obtained at the highest running speed. These findings suggest that a subject's SI will increase at faster running speeds. This assumption is supported by a study by Keller *et al.* that investigated the IFCP group distribution in a wide range of running speeds from 1-7 $m \cdot s^{-1}$ (23). IFCP group distribution changed from predominantly IRFC at running speeds up to 5 $m \cdot s^{-1}$ to predominantly IMFC at speeds above 5 $m \cdot s^{-1}$. This shows that running speed may influence IFCP. However, Keller *et al.* did not report within-subject IFCP alterations due to a changed running speed. Assessing these intra-individual alterations in SI, determined with a sensitive pressure plate, should provide a better insight in the relationship between running speed and SI.

Apart from running speed, the shoe or contact surface can influence running biomechanics (14,30,32,33) and in some extreme cases might even change ones strike pattern (35). If a study wanted to assess IFCP and intrinsic running technique differences, not confounded by differences in footwear but in realistic shod conditions, subjects should run in a neutral type shoe. This was not the case in the 'marathon' studies (19,24,25) in which subjects wore their own running shoes which could have influenced IFCP differences between subjects. Also Gruber *et al.* (18) found that when habitual rearfoot strikers ran barefoot on a soft surface, not all runners changed their IFCP, indicating it is not just the presence or absence of a shoe but also the contact surface properties that influence the chosen IFCP.

The goals of this study are first to accurately assess IFCP during steady state (=constant pace) shod running for a large group of long distance runners, wearing the same type running shoe, using high speed plantar pressure measurements. Second we want to assess the within-subject effect of running speed on the IFCP type over a wide range of relevant running speeds. Our **hypotheses** are that most runners show an IRFC but with increasing velocity some of these runners make a shift towards an IMFC or IFFC. Besides the previously stated main research purposes a secondary intention was to look for differences in the peak vertical instantaneous loading rate (VILR) between IFCPs, because VILR is a variable that has been associated with musculoskeletal overloading in running.

METHODS

Subjects

Fifty-five runners (40♂ and 15♀) of recreational and competitive level were recruited from local running clubs and the Ghent University and its surrounding community. For the male subjects mean ± SD age was 28.6 yrs. ±8.1; bodymass 71.9 kg ±5.8; height 1.80 m ±0.05; training pace 3.54 $m \cdot s^{-1}$ ±0.34; weekly training volume 41.2 km ±22.9 and years of running experience 8.7 yrs. ±5.9. For the female subjects mean ± SD age was 28.2 yrs. ±8.3; bodymass 59.4 kg ±4.5; height 1.67 m ±0.05; training pace 3.05 $m \cdot s^{-1}$ ±0.30; weekly training volume 36.3 km ±15.2 and years of running experience 9.3 yrs. ±5.2. All subjects were aged between 18 and 58 years, had a shoe size between US Men's 6.5 and 11 and had a weekly training volume of 15 km or more. No runners were currently injured or had sustained any injuries that required a temporary or full cessation of running within three months prior to participation in the study. Written informed consent was obtained prior to participation in this study. Ethical approval for the study was obtained from the ethical committee of the Ghent University hospital.

Protocol and experimental setup

Prior to the running tests, subjects completed a questionnaire to assess running habits (e.g. weekly training volume, endurance run training speed and years of running experience). After a short warming-up of 5-10 minutes, which also served as habituation to the test shoe and experimental setup, subjects were asked to perform several running bouts over a 25m instrumented walkway, at 4 speeds: 3.2, 4.1, 5.1 and 6.2 $m \cdot s^{-1}$. Those speeds were selected to represent the speed range in the training program of an endurance runner (13).

To counter a possible bias of shoe type or shoe construction on the subjects' running style, all subjects wore the same shoes (Li Ning Magne (ARHF041)). The shoes were modified for optimizing plantar pressure measurements by substituting a flat outsole and filling in the midfoot region of the midsole. The midfoot region was filled in with a standard EVA foam, with the same hardness as the original outsole, to level out the gap between the heel and forefoot part of the shoe. A flat outsole was achieved by grinding off the original outsole profile and replacing it by a new non-profile even outsole (shoe characteristics of size US 10: forefoot width 11.2, heel width 9, sole length 31.8, heel thickness 2.9 and a heel toe offset of 1.15 cm; impact testing results following ASTM F-1976-06 procedures ~950 N or peak g of ~11.5 g). No runners indicated feeling uncomfortable with the test shoes or with the selected speeds and results from the questionnaire did not indicate a systematic difference in habitual shoe type between different IFCP groups.

Before every speed block subjects practiced running at the selected speed by following pacing lights attached to the side of the runway. GRF (1000 Hz) and plantar pressures (500 Hz) were measured by a built in 2m force plate (AMTI, Watertown, MA, USA) mounted with a 2m pressure plate on top (Footscan, RSscan International, Olen, Belgium). Running speed was measured with a distance laser (1000 Hz, Noptel Oy, Oulu, Finland). During the experiment subjects were given feedback on their running speed based on infrared timing gaits. For each speed and foot side three successful trials per subject were collected. Trials were rejected if the speed measured from the timing gates was outside of a ±0.2 $m \cdot s^{-1}$ range of the target speed, if the subject accelerated or decelerated during the measurement, if the feet were in contact with the edges of the pressure plate or if it was obvious that the subject was targeting the force plate.

Data processing

Frequency analysis of GRF signals of running trials in our setup showed resonance frequencies above 80 Hz. GRF data were filtered using a Butterworth 2^{nd} order low pass filter with a cutoff frequency of 80 Hz. Residual analysis of GRF signals and qualitative assessment of the over/under filtering effect of different cutoff frequencies (range 50-100 Hz, with 10 Hz intervals) on the force-time signals were done to determine the optimal cutoff frequency. The pressures were dynamically calibrated with the vertical force signal. This means that the summed pressure of the entire contact surface was scaled to correspond with the GRF (Footscan 7 Gait 2^{nd} generation software).

Contact time was defined as the time when GRF was above 5N. Peak vertical instantaneous loading rate (VILR), which is a frequently used impact measure (9, 31), was calculated as the maximal value of the first derivative, over a 0.004 s interval, of the vertical GRF component during the initial contact phase (first 0.050 s of foot contact) and was normalized to subjects' bodyweight ($BW \cdot s^{-1}$).

Strike index (SI) determination

The classic SI method uses force plate data for COP calculations and kinematic data to locate the foot on the force plate. In this study, COP data was obtained with a more sensitive pressure plate (sensor size 0.5088 x 0.762 cm)(Footscan, RSscan International, Olen, Belgium). COP coordinates were expressed as a percentage of shoe length where the longitudinal axis of the shoe was determined by the Footscan 7 software. For normalization to shoe length we assumed that the most distal COP-point was at the normalized total foot length. Based on the COP-position at initial contact, a SI was defined and foot contacts were identified as IRFC (SI of 0-0.333), IMFC (SI of 0.334-0.666) or IFFC (SI of 0.667-1).

Statistical analysis

Intraclass correlation coefficients (ICC) were calculated for SI, VILR and contact time using SPSS Statistics 21 (SPSS Inc., Chicago, IL, USA) for trials within each footside and condition. All ICC's were higher than 0.8 indicating low variability across trials. For further statistical analysis these parameters were averaged per subject, speed and footside. If for a subject not all 3 trials could be assigned to the same IFCP group, the average value for statistical analysis was calculated based on the trials of the most frequent (2 out of 3 trials) IFCP. All further statistical procedures were conducted using MLwiN 2.27 statistical analysis software (University of Bristol, Bristol, UK) with significance level set at $p<0.05$. Multilevel linear regression models (three levels: participant-footside-measurement) were constructed in order to determine the within-subject effect of speed on SI and the between IFCP group differences in VILR and contact time. These models combined the significant main and interaction effects ($p<0.05$) of speed, footside and IFCP group. For the pairwise comparisons between the different speed conditions and the different IFCP groups a Bonferroni correction was done.

RESULTS

Initial foot contact pattern group distribution

Based on the SI three IFCP groups could be classified: runners with an IRFC, an IMFC or an IFFC. A visual representation of SI and the IFCP group for each subject in each speed condition is given in figure 1. Some subjects showed a different color scale for their left and right foot indicating an asymmetry in IFCP (fig. 1). An asymmetrical IFCP occured in 11% of runners at 3.2 $m \cdot s^{-1}$, in 9% at 4.1 $m \cdot s^{-1}$, in 25% at 5.1 $m \cdot s^{-1}$ and in 31% of runners at 6.2 $m \cdot s^{-1}$.

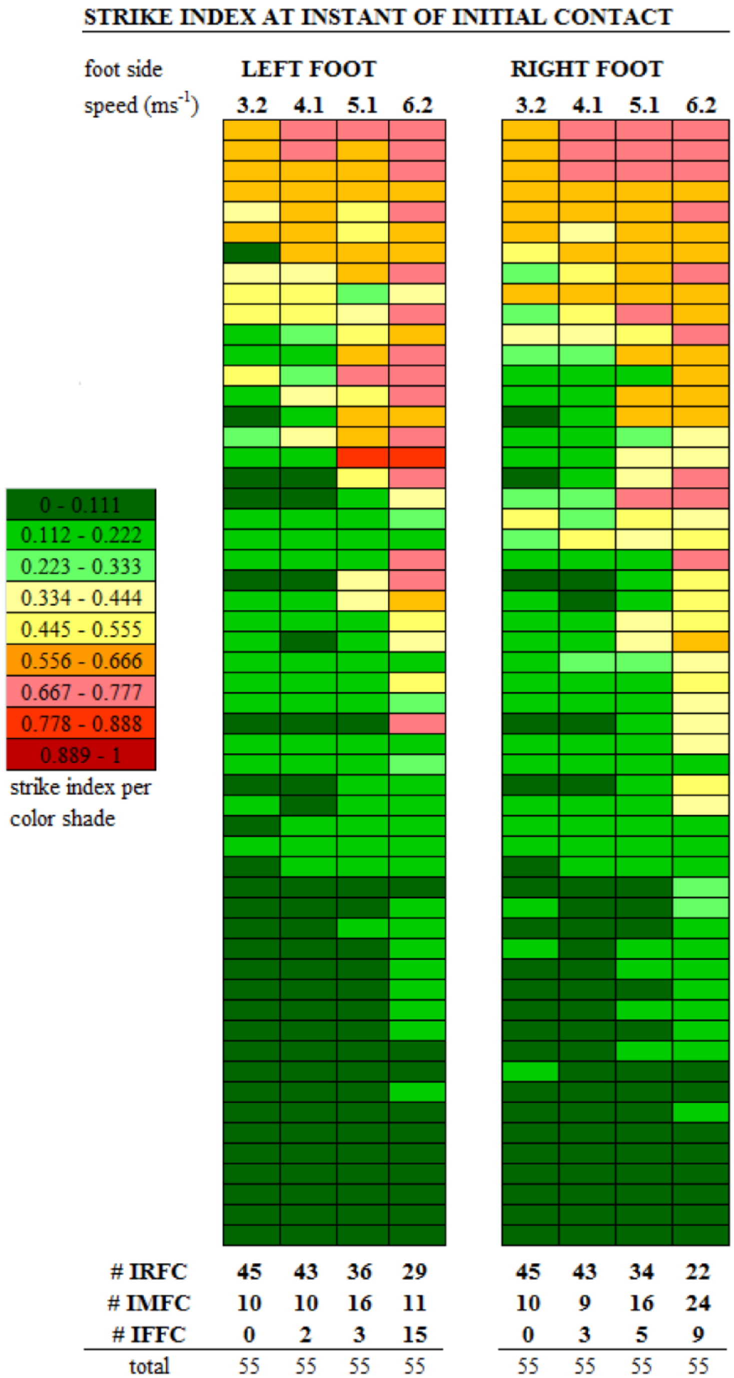

Figure 1: *SI per subject, per speed, per foot side. SI is indicated by a color scale. Green cells indicate an IRFC. Yellow cells indicate an IMFC. Red cells indicate an IFFC. Each horizontal line represents data from the same subject for both left and right foot. Subjects are vertically sorted in such way that the upper horizontal line represents data from the subject with the highest mean SI and the lower horizontal line represents data from the subject with the lowest mean SI over both feet and all speed conditions.*

Within-subject effect of speed on strike index

A three-level linear regression model (subject, footside and measurement) was constructed with categorical parameters footside (left as reference category) and speed (slowest speed as reference category), and SI as the dependent variable. The non-significant interaction terms, that subsequently were deleted from the model, model parameters and main effects are presented in table 1. We found a significant main effect of speed on SI. Post-hoc analysis revealed a significant difference in SI between about all speed conditions (chi²≥22.6, p<0.001) except between 3.2 m·s^{-1} and 4.1 m·s^{-1} (chi²=1.401, p=0.237). This confirms an increase in SI when the running speed increases. (Table 1)

Table 1: *Results of the statistical analysis. For each test non-significant interaction effects (that subsequently were deleted from the model), model parameters slope (β_0) and standard error (S.E.) and main effects are reported.*

Test 1: Within subject effect of speed on SI					
Non-significant interaction parameters	**chi²**	**p**	**Model parameters**	**β_0**	**S.E.**
speed*footside	0.339	0.999	constant	0.190	0.027
			speed 4.1 m·s^{-1}	0.018	0.015
Main effects	**chi²**	**p**	speed 5.1 m·s^{-1}	0.090	0.015
footside	1.762	0.184	speed 6.2 m·s^{-1}	0.189	0.015
speed	193.6	<0.001	footside_RI	0.018	0.014

Test 2: Between IFCP group differences in contact time (ms)					
Non-significant interaction parameters	**chi²**	**p**	**Model parameters**	**β_0**	**S.E.**
speed*footside*IFCP	3.553	0.999	constant	253.0	1.825
speed*footside	4.975	0.547	speed 4.1 m·s^{-1}	-35.0	0.992
IFCP*footside	0.885	0.989	speed 5.1 m·s^{-1}	-64.6	1.023
Speed*IFCP	34.902	0.861	speed 6.2 m·s^{-1}	-88.7	1.138
			footside_RI	-0.8	0.776
Main effects	**chi²**	**p**	IMFC	-11.9	1.603
footside	1.152	0.283	IFFC	-10.9	1.950
speed	6827.351	<0.001	Atypical IRFC	-8.8	1.542
IFCP	60.272	<0.001			

Test 3: Between IFCP group differences in VILR (BW·s^{-1})					
Non-significant interaction parameters	**chi²**	**p**	**Model parameters**	**β_0**	**S.E.**
speed*footside*IFCP	2.898	0.999	constant	108.5	7.444
speed*footside	2.326	0.887	speed 4.1 m·s^{-1}	42.6	4.701
IFCP*footside	0.791	0.992	speed 5.1 m·s^{-1}	95.7	4.844
speed*IFCP	19.324	0.999	speed 6.2 m·s^{-1}	161.6	5.373
			footside_RI	-0.9	3.950
Main effects	**chi²**	**p**	IMFC	4.7	7.416
footside	0.056	0.813	IFFC	-60.1	9.125
speed	985.757	<0.001	Atypical IRFC	37.6	7.188
IFCP	115.749	<0.001			

There is a group which we will call 'transition' runners in which an increase in speed caused a shift to another IFCP. Most runners shifted to a more anteriorly located SI. Some runners performed one such transition (37%) while others showed two (11%). However, there is a large group of runners that showed an IRFC over all running speeds (46 %) as well as a small group of runners that showed an IMFC over all running speeds (6%). In these subjects the increased running speed did not cause a shift towards another IFCP group.(Table 2)

Table 2: *Percentage of runners that show the same IFCP in all running speeds and percentage of runners that show a shift to another IFCP with an increase in running speed.*

	SI@IC	
	left	**right**
No transition		
IRFC over all speeds	52.7%	40.0%
IMFC over all speeds	3.6%	7.3%
IFFC over all speeds	0%	0%
1 transition to a more anteriorly located IFCP		
IRFC to IMFC	14.5%	32.7%
IRFC to IFFC	5.5%	3.6%
IMFC to IFFC	9.1%	9.1%
2 transitions to a more anteriorly located IFCP		
IRFC to IMFC to IFFC	9.1%	5.5%
other	5.5%	1.8%

Atypical initial rearfoot contact patterns

Most runners showed an IRFC when collapsed across running speed (68%). Typical IRFCs show a COP trajectory with the initial contact at the posterior lateral shoe sole side, after which the COP moves rapidly towards the midline of the shoe sole. When processing the COP data we noticed that some runners with an IRFC showed COP trajectories that clearly differed from the typical IRFC COP pattern (fig. 2). A qualitative assessment was done of the COP trajectory, plotted over the footprint in the Footscan software, of all foot contacts at 3.2 $m{\cdot}s^{-1}$ (55 subjects, 3 left and 3 right foot contacts per subject, minus 3 failed measurements resulting in 327 foot contacts in total), which is the speed that best matches the runners' training pace. An atypical IRFC COP trajectory was defined when initial contact was made in the rearfoot zone, immediately followed by a fast anterior COP movement along the lateral shoe margin into the midfoot zone, which was then followed by the COP moving medially in the midfoot zone (fig. 2). Based on this qualitative assessment 76 of 328 foot contacts were qualitatively selected as atypical IRFC, 193 as typical IRFC and the remaining 58 as a typical IMFC or IFFC.

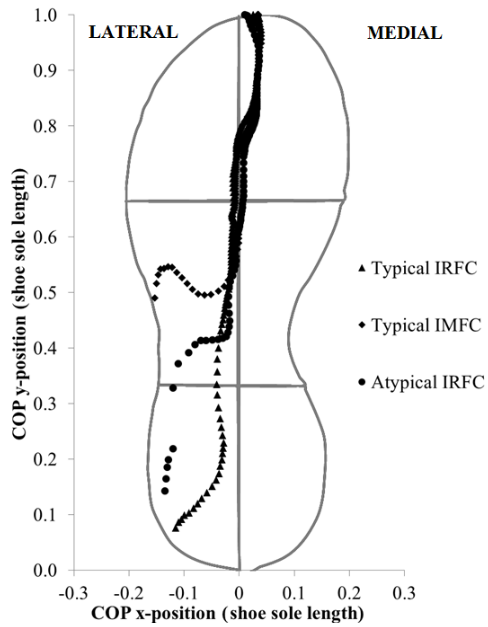

Figure 2: *Left foot COP trajectories from a typical IRFC trial, a typical IMFC trial and an atypical IRFC trial.*

Apart from such a qualitative assessment we also wanted to be able to identify the atypical IRFC patterns using a quantitative functional measure. This was obtained from differences in the foot unroll timing parameters. The timing of a foot unroll can be subdivided based on some specific events during foot contact such as initial foot contact, first metatarsal contact, initial foot flat contact, heel off, last foot contact (7). In barefoot IRFC first metatarsal contact occurs at approximately 8% of contact time (7). When running shod the foot touches the ground in a more dorsiflexed position (40) so first metatarsal contact will probably occur later, if plantarflexion velocity remains the same. The fast anteriorly moving COP in the atypical subjects indicates an initial fast shift of pressure towards the forefoot region with a first metatarsal contact occurring sooner in such patterns than in the typical IRFC patterns, providing an objective measure to distinguish between the 2 categories. In IFFC or IMFC running first metatarsal contact concurs with initial contact.

Time of first metatarsal contact was defined as time between initial contact and the instant of first plantar pressure in the metatarsal zone (7). For both the atypical IRFC and typical IRFC foot contacts the first metatarsal contact showed a double-peaked frequency distribution. This indicates that based on the time of first metatarsal contact two groups can indeed be identified in the IRFC foot contacts based on this temporal variable. The time of first metatarsal contact also showed high significant intra-class correlation (ICC) between the three trials of each foot ($p<0.001$, left feet ICC=0.910; right feet ICC=0.936).

In the typical IRFC foot contacts (193 of 327 foot contacts), which were first identified by a qualitative assessment of the COP trajectories, first metatarsal contact occurred at 11.8 ±2.9% of contact time. In the atypical IRFC foot contacts (76 of 327 foot contacts), as first identified by the qualitative assessment, first metatarsal contact occurred at 4.0 ±2.0% of contact time. This means that when first metatarsal contact occurs before 6.0 % of contact time (= mean time of first metatarsal contact typical IRFC – 2 standard deviations) there is a good chance that this pattern is an atypical IRFC pattern. Nevertheless, some atypical IRFC patterns showed first metatarsal contact up to 8% of contact time (mean atypical IRFC +2 standard deviations). Consequently, for foot contacts with a first metatarsal contact between 6% and 8% of contact time a visual qualitative assessment of the COP pattern is still needed for a correct classification. Of the 327 foot contacts, 35 had a first metatarsal contact between 6 and 8% of contact time. Based on the qualitative assessment of the COP trajectories, 18 were identified as typical IRFC and 17 as atypical IRFC.

At the higher running speeds, above training pace, the atypical patterns were also identified based on the qualitative assessment. If the atypical pattern was shown in more than 1 of the 3 trials per speed per foot, the runners was classified as an atypical IRFC runner for this specific speed and footside. Forty-two % of runners showed this atypical IRFC pattern at some point over all speeds. Even 9% of runners showed the atypical IRFC pattern in all speed conditions for one footside and 4% showed the atypical IRFC pattern in both feet in all speed conditions. At 3.2 $m \cdot s^{-1}$ 58% of runners showed typical IRFC and 24% an atypical IRFC, at 4.1 $m \cdot s^{-1}$ 55% of runners showed a typical IRFC and 24% an atypical IRFC, at 5.1 $m \cdot s^{-1}$ 44% of runners showed a typical IRFC and 20% an atypical IRFC, at 6.2 $m \cdot s^{-1}$ 31% of runners showed a typical IRFC and 15% an atypical IRFC. An adjusted version of figure 1, with indication of the runners that showed the atypical

IRFC pattern, is available as supplemental digital content 1 (see Figure, SDC 1, SI at initial contact per subject, per speed, per footside, with indication of the runners that show the atypical IRFC).

Between group differences in VILR and contact time

Based on the SI and the assessment of the atypical IRFC patterns we classified 4 groups of runners. Although not stated as one of the primary research goals of this study, between group differences in contact time and VILR were assessed, also to help found the identification of the atypical IRFC as a distinct fourth IFCP. A three-level linear regression model (subject, footside and measurement) was constructed with following categorical parameters: footside (left as a reference category), speed (slowest speed as reference category), IFCP (typical IRFC as a reference category) and **contact time** (expressed in milliseconds) as the dependent variable. Results of this analysis are presented in table 1. We found a significant main effect of speed and IFCP group on contact time. Post-hoc analysis revealed a significant difference in contact time between all speed conditions ($chi^2 \geq 536.411$, $p<0.001$) where contact time decreased with increasing speed. Post-hoc analysis also showed that the typical IRFC group has longer contact times than the other IFCP groups ($chi^2 \geq 31.027$, $p<0.001$) and that the IMFC group has shorter contact times than the atypical IRFC ($chi^2=4.275$, $p=0.039$). (Fig. 3)

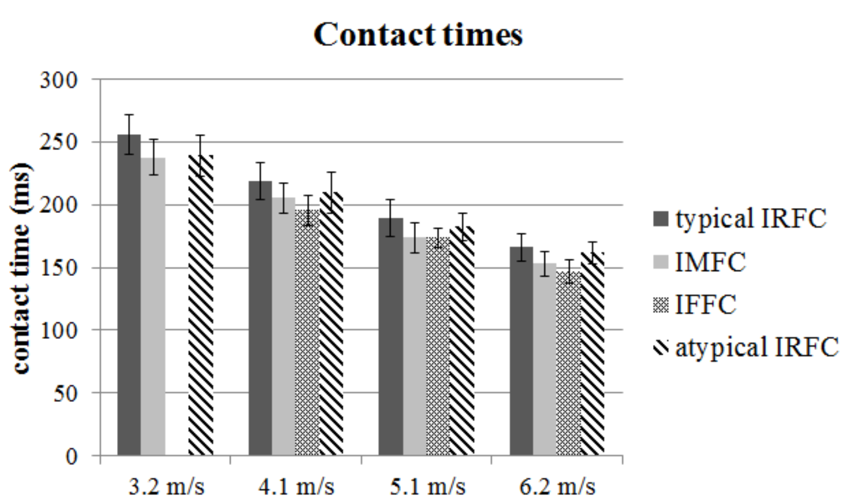

Figure 3: *Mean ± standard deviation of the* ***contact times*** *(s) per initial foot contact pattern (IFCP) group per speed, collapsed over footside. Notice that there were no IFFC at 3.2* $m{\cdot}s^{-1}$.

Another three-level linear regression model (subject, footside and measurement) was constructed with following categorical parameters: footside (left as a reference category), speed (slowest speed as reference category), IFCP (typical IRFC as a reference category) and **VILR** (expressed in $BW \cdot s^{-1}$) as the dependent variable. The results of this analysis are presented in table 1. We found a significant main effect of speed ($chi^2=985.757$, $p<0.001$) and IFCP group ($chi^2=115.749$, $p<0.001$). Post-hoc analysis revealed a significant difference in VILR between all speed conditions ($chi^2 \geq 124.455$, $p<0.001$) where VILR increased when speed increased. Post-hoc comparison between the IFCP groups showed significant differences in VILR between all IFCP groups ($chi^2 \geq 22.420$, $p<0.001$) except between the typical IRFC and the IMFC groups ($chi^2=0.404$, $p=0.525$). The highest VILR were seen in the atypical IRFC group and the lowest VILR in the IFFC group. (Fig. 4)

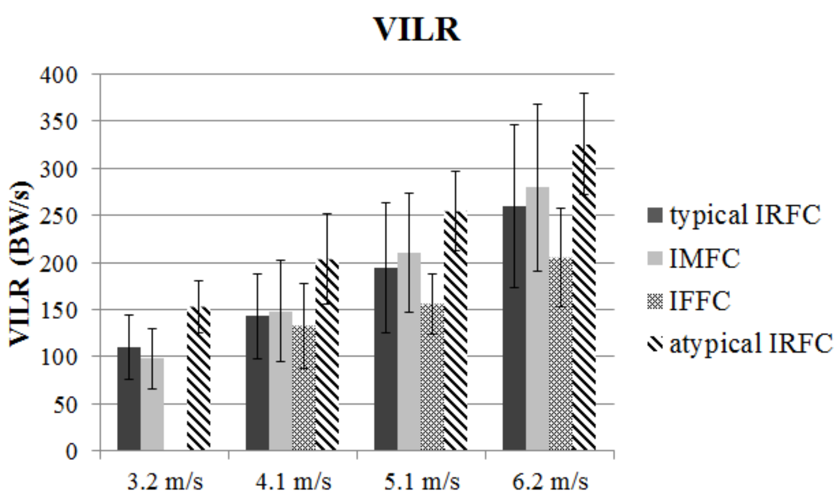

Figure 4: *Mean ± standard deviation of the* ***maximal loading rates*** *($BW \cdot s^{-1}$) per initial foot contact pattern (IFCP) group per speed, collapsed over footside. Notice that there were no IFFC at 3.2 $m \cdot s^{-1}$.*

DISCUSSION

IFCP group distribution

The first purpose of this study was to accurately assess the IFCP during steady state shod running for a group of long distance runners using 500 Hz pressure measurements underneath the shoe, as such a system gives a more accurate COP at low vertical GRF and allows direct localization of the COP on the plantar side of the shoe sole.

The resulting IFCP group distribution of 82% IRFC, 18% IMFC at 3.2 $m \cdot s^{-1}$ and 46% IRFC, 32% IMFC, 22% IFFC at 6.2 $m \cdot s^{-1}$ were mainly in accordance with previous research that determined IFCP groups with the SI method (5,23). As in Keller *et al*. (23), more than 50% of our subjects showed an IMFC or IFFC when running at about 6 $m \cdot s^{-1}$. Keller *et al.* however, reported higher percentages of subjects showing an IMFC or an IFFC (86%) versus IRFC (14%) when running at 6 $m \cdot s^{-1}$. A possible explanation for this discrepancy could be that in the study by Keller *et al.* not all subjects were able to run at 6 $m \cdot s^{-1}$. More subjects were presented at the slower running speeds than at speeds faster than 5 $m \cdot s^{-1}$. In our study all subjects were able to run up to 6.2 $m \cdot s^{-1}$.

Within-subject effect of speed on strike index

The second purpose of this study was to assess the within-subject effect of running speed on the SI. With increasing speed SI significantly increased, indicating that when subjects ran faster they tended to touch the ground more anteriorly on the shoe sole. This is supported by a previous study by Nigg *et al*. in heel-toe runners (~IRFC) (32). Different kinematic changes may occur (e.g. more flexed knee or ankle etc.), but foot angle would be a variable that specifically affects SI. Further research should clarify which specific speed-induced kinematic changes are related to a change in SI and if these speed-induced adaptations differ between the different IFCP groups.

In this study, 52% of runners showed the same IFCP over all running speeds while other subjects were termed 'transitional' runners, that made the transition from an IRFC to an IMFC (24%) or IFFC (5%) or from an IMFC to a IFFC (9%). Some runners even showed a double transition from an IRFC over an IMFC to an IFFC (7%). These ‘transitional’ runners create the complex task of a shoe design that, both at low and high running speeds, is functionally adjusted for changes in IFCP.

Previous research reported larger percentages of IMFC and IFFC patterns during marathon and half marathon racing events in elite distance runners compared to recreational runners (19,24), suggesting there might be a performance benefit with IMFC or IFFC patterns. Our results however, suggest that the greater percentages of IMFC and IFFC in elite runners might just be a consequence of their faster running speeds rather than these IFCPs being beneficial for performance. This statement is supported by research by Larson *et al.* (25) who found no significant differences in marathon time between the different foot strike pattern groups.

Atypical initial rearfoot contact patterns

A main finding of this study was the splitting of IRFC into two groups: atypical and typical IRFC. Based on a qualitative assessment of the COP patterns 22% of runners showed this pattern at two or more speed conditions and 18% of all runners showed this pattern with both feet in 2 or more speed conditions. This indicates that this pattern should indeed be considered as a distinct IFCP.

The atypical IRFC were characterized by an initial fast anterior displacement of the COP along the lateral shoe margin. These patterns have not been described before. At the lowest speed of 3.2 $m \cdot s^{-1}$ these atypical IRFC are characterized by an earlier first metatarsal contact (4.0 ±2.0% of contact time) compared to the typical IRFC (11.8 ±2.9% of contact time). This timing can be used as a criterion to distinguish between the atypical IRFC and the typical IRFC. However, for the foot contacts with a first metatarsal contact between 6 and 8% of contact time a qualitative assessment of the COP trajectory is needed. Other criteria, based on kinematics and/or COP based calculations, could also provide a good, or even better classification into different IFCP categories.

Based on the previously reported higher loading variables in IRFC patterns some authors have suggested that a switch from an IRFC to an IFFC or IMFC could possibly be beneficial towards external loading and/or injury susceptibility (29,34). Research that supports these suggestions reports a reduction in impact loading with an IMFC pattern (2,3) or IFFC pattern (11,27). However, not all studies support these findings (5,17,26,34,36) and neither does our research. This discrepancy may partially be explained by atypical and typical IRFC.

As IFCP is frequently associated with the impact like character of the foot contact, VILR was assessed. This showed that apart from the atypical COP patterns, at all studied running speeds, runners with an atypical IRFC were also characterized by higher VILR values than runners with typical IRFC. In the atypical IRFC the mean VILR increased from 153.0 $BW \cdot s^{-1}$ at 3.2 $m \cdot s^{-1}$ to 325.2 $BW \cdot s^{-1}$ at 6.2 $m \cdot s^{-1}$. In the typical IRFC the mean VILR increased from 109.2 $BW \cdot s^{-1}$at 3.2 $m \cdot s^{-1}$ to 259.6 $BW \cdot s^{-1}$ at 6.2 $m \cdot s^{-1}$. No significant difference in VILR was found between the typical IRFC and the IMFC and IFFC. The reported VILR values, which increased with running speed, are in line though with previous research (32,20,40). However, other studies (9,26) reported lower VILR. This discrepancy might be due to the lower cutoff frequency of 50Hz that was used to filter GRF data in these studies. This might have caused more smoothing of the initial vertical GRF signal resulting in lower VILR. If the atypical IRFC patterns, with larger VILR, would not have been identified and instead treated as typical IRFC patterns, the entire IRFC pattern group would have showed larger VILR than both the typical IRFC and the IMFC.

It has been shown that increased stride length results in an increase in VILR (20). Such findings could support the reasoning that the lower VILR found in runners with an IFFC or IMFC might be due to the shorter stride lengths (and higher step frequencies) found in these runners (2,16). However the reported differences in stride length and frequency between IRFC and IMFC or IFFC are much smaller (<2%) than the range of stride lengths that show an increase in VILR. Therefore we believe that other factors than just the difference in stride lengths, such as segment and joint positions and speeds at touchdown, should be assessed to help explain the observed VILR differences.

When running with an IFFC or IMFC the impact of running is partially attenuated by an initial ankle dorsiflexion movement (27). With a typical IRFC this is done by the cushioning properties of both the heel's fat pad and shoe midsole (6). A possible explanation for the higher VILR associated with an atypical IRFC could be that when running with an atypical IRFC neither of these 'strategies' of impact reduction are fully used. Initial contact is made with the rearfoot, limiting the possible use of an 'ankle-dorsiflexion strategy' and the early first metatarsal contact and the fast anterior COP movement indicates the limited use of the cushioning properties of the heel partition. Future research may verify these hypotheses.

It was shown that the typical IRFC group have longer contact times than the other IFCP groups. A possible explanation for these differences can be found in the time between initial foot contact and first metatarsal contact. This first phase of foot contact is shorter in the atypical IRFC and absent in the IMFC and IFFC. Future research should assess if any other differences in running style, running kinetics or kinematics exist between the IFCP groups and could explain the observed differences in contact time and VILR.

Finally our study has the following limitations. All subjects wore the same neutral shoe to counter the possible bias of shoe type on IFCP. However, this means that some subjects had to run in a shoe type different from their habitual running shoe type. This could have influenced their 'natural' IFCP. The time of first metatarsal contact allows to distinguish between the typical IRFC and the atypical IRFC. However for 10% of foot contacts (those with a first metatarsal contact between 6 and 8% of contact time) an additional qualitative assessment of the COP trajectory was needed. Other criteria based on kinematics and/or COP calculations might provide the same or even better classification.

This study introduced a refined SI determination method, with COP based on plantar pressure measurements, and identified a group of atypical IRFC runners that are characterized by a fast first metatarsal contact and high VILR values. This methodological refinement and IFCP group determination could help future research to reduce the lack of uniformity in the current research regarding the relationship between IFCP and variables of interest.

Summary

IFCP is influenced by speed as some subjects changed towards a more anterior located IFCP with increasing speed. Also the presented methods allowed to discriminate an atypical IRFC versus a typical IRFC, characterized by different COP patterns in the initial part of stance. This resulted in higher VILR for the atypical IRFC group, but no difference in VILR between the typical IRFC and the IMFC groups. These findings challenge and underline the need for future research linking IFCP, measured accurately over a relevant velocity range, to injury susceptibility, performance, economy or specific footwear needs.

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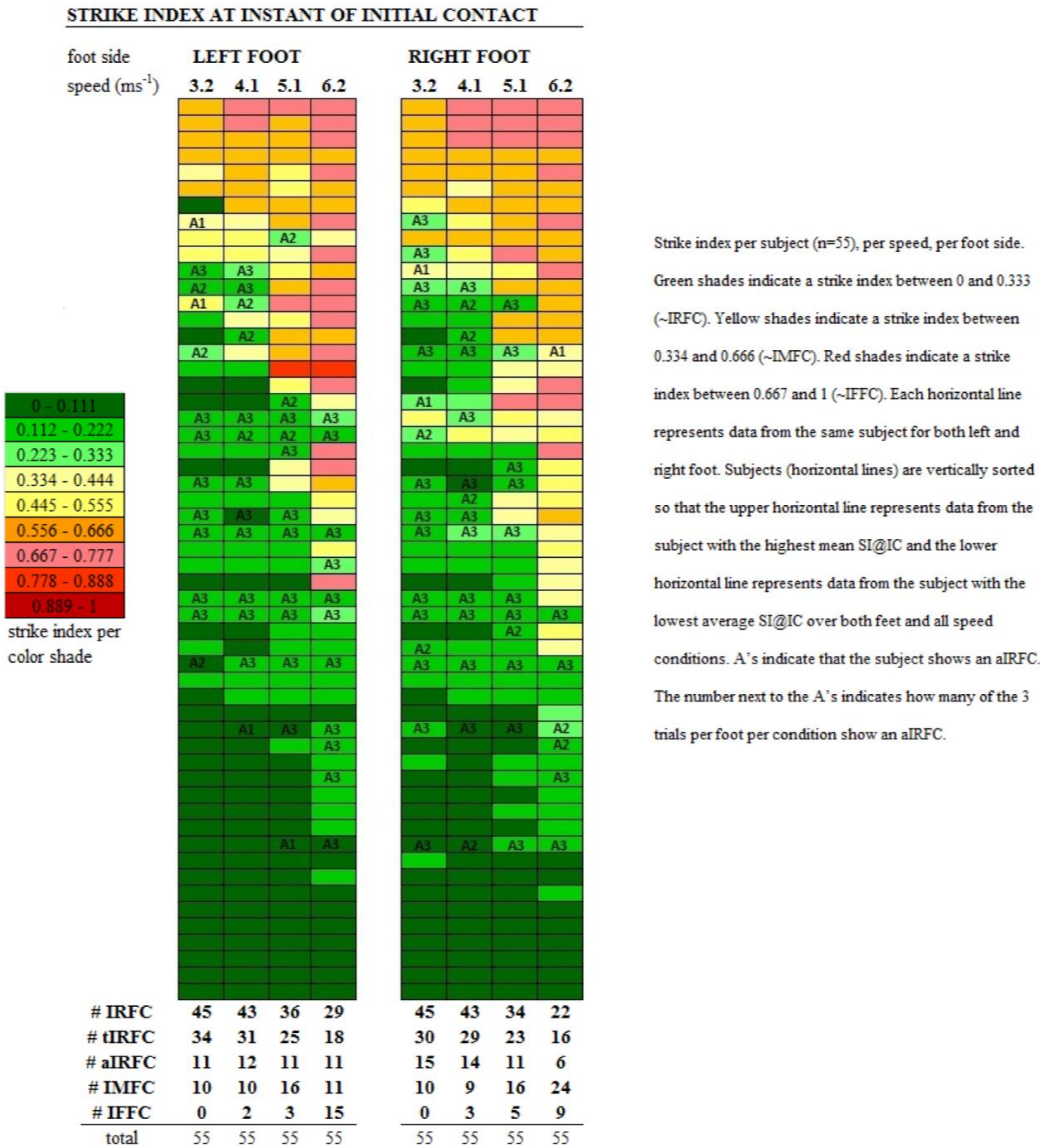
Conflict of interest

The authors have no conflicts of interest.

Supplemental digital content



Supplemental digital content 1: *Strike index per subject (n=55), per speed, per foot side. SI is indicated by a color scale. Green cells indicate a strike index between 0 and 0.333 (~IRFC). Yellow cells indicate a strike index between 0.334 and 0.666 (~IMFC). Red cells indicate a strike index between 0.667 and 1 (~IFFC). Each horizontal line represents data from the same subject for both left and right foot. Subjects are vertically sorted so that the upper horizontal line represents data from the subject with the highest mean SI and the lower horizontal line represents data from the subject with the lowest mean SI over both feet and all speed conditions. The letter 'A' indicate that the subject shows an atypical IRFC. The number next to letter A indicates how many of the 3 trials per foot per condition show an atypical IRFC.*

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STUDY 2

Initial foot contact and related kinematics affect impact loading rate in running

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ABSTRACT

Purpose. This study assessed kinematic differences between different initial foot contact patterns (IFCP) and their relationship with peak vertical instantaneous loading rate (VILR) of the ground reaction force (GRF). **Methods.** Fifty-two runners ran at 3.2 $m \cdot s^{-1}$ while we recorded GRF and lower limb kinematics and determined IFCP category: Typical or Atypical initial rearfoot contact pattern (IRFC), and initial midfoot contact pattern (IMFC). **Results.** Typical IRFC had longer contact times and a lower leg stiffness than Atypical IRFC and IMFC. Typical IRFC showed a dorsiflexed ankle (~7.2°) and posteriorly titled foot (~20.4°) at initial contact while IMFC showed a plantar flexed ankle (~-10.4°) and a more horizontal foot (~1.6°). Atypical IRFC showed initial ankle and foot configurations in between Typical IRFC and IMFC but had the highest VILR. For the IRFC (Typical and Atypical IRFC), the initial foot angle showed the highest correlation with VILR (r=-0.68). The observed higher VILR in Atypical IRFC could be related to both distal ankle and foot kinematics and global running style that indicate a limited use of known kinematic impact absorbing ‘strategies’ such as initial ankle dorsiflexion in IMFC or initial ankle plantar flexion and lower leg stiffness in Typical IRFC. **Conclusions.** Typical IRFC, Atypical IRFC and IMFC are considerably different running styles accompanied by differences in VILR.

INTRODUCTION

A common way to classify running style is using the initial foot contact pattern (IFCP). Based on the first contact with the ground, IFCPs can be categorized as initial rearfoot (IRFC), midfoot (IMFC) or forefoot (IFFC) contact. In shod distance running approximately 75% of runners show an IRFC, 20% an IMFC and 5% an IFFC (5, 6, 13, 15). IFCP is related to initial foot positioning and the subsequent ankle and foot kinematics (2, 9, 22, 25). However, also more proximal movements (e.g. hip and knee angles at initial foot contact) could relate to a certain IFCP (1). In a recent study (5) we have found that 44% of the recorded IRFC contacts showed atypical center of pressure (COP) patterns. We named these contacts ‘Atypical IRFC’. These Atypical foot contacts had an initial COP at the rear 1/3 of the foot (IRFC), but showed an early first metatarsal contact and an initial fast anterior COP displacement along the lateral shoe margin into the midfoot zone, as opposed to an initial medial-forward COP movement towards the midline of the foot in a Typical IRFC. After this very short initial foot contact phase (about 4% of contact time) the COP moves, similarly to an IMFC, medially into the midfoot zone before further moving anteriorly towards the toes. Apart from the very short, fast initial COP movement, this pattern resembles an IMFC COP pattern.

The short initial foot contact phase in the Atypical IRFCs could be related to a flatter foot position at initial contact. Therefore the question arises how these Atypical IRFC would be classified using a kinematic method to determine IFCP based on the foot-to-ground-angle at initial foot contact (2). The fast initial COP movement towards the midfoot region in Atypical IRFCs seems only feasible with a ‘flatter’ foot position, which would resemble an IMFC (2). Therefore, we compared distal kinematics between the Typical IRFC, Atypical IRFC and the IMFC. However, IFCP could also relate to more global running kinematics (21), that are more closely related to the total body movement (e.g. contact time, knee flexion, leg stiffness, …). Breine *et al.* (5) indeed observed shorter contact times in IFFC and IMFC compared to IRFC, indicating that not only distal kinematics but also global running kinematics differ between the different IFCPs. Therefore, we also compared global running kinematics between the different IFCPs.

Although we hypothesize that the Atypical IRFC resembles more an IMFC than a Typical IRFC, Atypical IRFC are characterized by higher peak instantaneous loading rates of the vertical GRF (VILR) than Typical IRFC and the IMFC (5). This is important, since a high VILR has been shown to relate to an increased risk for lower limb stress fractures (18, 29) and has been shown a more reliable parameter to assess impact severity than the magnitude of the transient ‘impact’ peak in the vertical GRF (23). Several kinematic differences between the IFCPs must relate to the observed VILR differences. The most logical differences would be related to distal ankle and foot kinematics that are known to relate to impact severity. In Typical IRFCs the posteriorly inclined foot position and dorsiflexed ankle at initial contact induce an initial ankle plantar flexion (12) and deformation of the cushioned rear section of the shoe midsole and the fat pad of the heel. These are regarded as impact reducing ‘strategies’ or mechanisms in a Typical IRFC (8, 27, 28). These mechanisms are not (or less) possible in an IMFC and IFFC due to the ‘flatter’ foot positioning. In an IMFC or IFFC an initial ankle dorsiflexion ‘strategy’ is regarded as a principal impact reducing mechanism (9, 16).

Since the Atypical IRFC have the highest VILR, it is of specific interest to what extent which of the aforementioned strategies are used with an Atypical IRFC. However, also other kinematic characteristics such as a higher vertical heel touchdown velocity (12), a more extended knee angle at touchdown (10), a lower step frequency (14) and even stiffer spring mass model characteristics, describing global running mechanics and the motion of the total body center of mass during foot contact (7, 17, 19), could relate to an increased impact severity.

The primary purpose of this study is to assess kinematic differences between Atypical IRFC, Typical IRFC and IMFC. We hypothesize that an Atypical IRFC resembles most to an IMFC. A secondary purpose of this study is to investigate a relationship between the observed kinematic differences and the impact severity, measured with VILR, via correlations and multiple linear regressions. We hypothesize that the main kinematic differences between the IFCPs will be found in the distal segments and joints. We also hypothesize that mainly these distal kinematics will correlate with VILR. We don’t have a specific hypothesis whether the Atypical IRFCs would use kinematic strategies more resembling to Typical IRFCs or more resembling to IMFCs.

METHODS

Participants

Fifty-two healthy runners (39 men and 13 women) were recruited and gave their written informed consent. We used the same dataset as in our previous research (5), except for 3 runners that were not retained due to insufficient 3D marker coordinate data to construct a kinematic model. Participant characteristics per IFCP group are shown in table 1. This study was approved by the ethical committee of the Ghent University hospital.

Table 1: *Mean ±SD participant characteristics per IFCP group*

	Number of participants		**Body mass (kg)**		**Height (m)**	
	men	*women*	*men*	*women*	*men*	*women*
Typical IRFC (n=31)	21	10	72.8 ± 5.7	58.6 ± 4.7	1.79 ± 0.05	1.65 ± 0.04
Atypical IRFC (n=11)	9	2	73.3 ± 6.0	64.4 ± 1.5	1.81 ± 0.04	1.75 ± 0.04
IMFC (n=10)	9	1	69.5 ± 5.2	54.7	1.80 ± 0.05	1.67

Protocol and experimental setup

After a short warming-up of ten minutes, participants performed several running bouts over a 25m runway at 3.2 $m{\cdot}s^{-1}$. All participants were first trained to run at the target velocity by following pacing lights alongside the runway, which were turned off during measurements. We checked if the participants ran within a 0.2 $m{\cdot}s^{-1}$ range of the target speed with infrared timing gates alongside the runway. Three left foot measurements for each participant were selected for analysis. Participants all wore the same shoes (Li Ning Magne (ARHF041)), modified to have a basic midsole and a flat outsole, without a gap or cavity between the heel and forefoot part of the shoe. For a detailed description of the test shoe we refer to the description in our previous study (5).

GRFs (1000 Hz) and plantar pressures (500 Hz) were measured with a built in 2m force plate (AMTI, Watertown, MA, USA) with a 2m pressure plate mounted on top (Footscan, RSscan International, Olen, Belgium). Three-dimensional lower body kinematics were recorded at 200 Hz with a 14-camera motion capture system (Qualisys AB, Gothenburg, Sweden). Retro-reflective markers were placed on anatomical landmarks of the thigh, shank and rearfoot. Holes were cut out of the experimental shoes, to apply the retro-reflective markers directly to the skin, which allowed us to measure foot movement and not shoe movement. A 3-segment kinematic model (rearfoot, shank, thigh) was constructed in Visual 3D (C-motion, Germantown, MD, USA). Knee and ankle joint and foot segment angles were normalized to the standing position, which was measured before the running trials. Apart from joint and segment angles, we also assessed the vertical touchdown velocity of the heel (v_{TDheel}).

GRF data were filtered with a Butterworth 2nd order low pass filter with a cut-off frequency of 80 Hz. Kinematic marker coordinate data were filtered with a cut-off frequency of 20 Hz. Knee and ankle flexion/extension moments were calculated using an inverse dynamics approach with Cardan sequence. Foot contact time was defined when vertical GRF was above a 10N threshold. VILR was calculated as the maximal value of the first derivative of the vertical GRF component during the initial impact phase (first 0.050s of foot contact). GRF and VILR were normalized to bodyweight (BW).

Spring-mass model characteristics vertical (k_{vert}) and leg stiffness (k_{leg}) were calculated based on maximal vertical GRF (Fmax), bodymass (m), leg angle at foot contact (strut from trochanter to metatarsals), and contact time (11, 20). Joint stiffness of the ankle (k_{ankle}) (during dorsiflexion) and the knee (k_{knee}) were calculated as the ratio of total change in joint moment and total change in joint angle during joint flexion (3), which resembles the average slope of the joint moment-angle curve. K_{knee} and k_{ankle} were normalized to bodyweight.

Each foot contact was defined as Typical IRFC, Atypical IRFC or IMFC based on a combination of strike index (6), time of first metatarsal contact and a qualitative assessment of the COP pattern. This approach was described in our previous research where the Atypical IRFC was first introduced (5). There was only one recorded IFFC trial, which was not retained for further analysis. Each foot contact was also defined as an IRFC, IMFC or IFFC using a kinematic method, based on foot-to-ground angle at initial contact, developed by Altman and Davis (2). With this method we defined an IMFC at an initial foot-to-ground-angle between -1.6 and 8.0°. As such, an IFFC was defined at a foot-to-ground angle <1.6° and an IRFC at >8.0°.

Statistics

All parameters of the three recorded trials were averaged per participant. If not all trials could be assigned to the same IFCP, the average value for statistical analysis was calculated based on the trials of the most frequent (two out of three trials) IFCP. ANOVAs with post-hoc analysis with Bonferroni correction were conducted to assess between-IFCP group differences (Typical IRFC vs. Atypical IRFC vs. IMFC) for selected spatiotemporal, kinematic and kinetic variables. Cohen's d effect sizes (d) and 95% confidence intervals (CI) of the mean difference between the different IFCPs were reported where statistical significance was reached. All statistical analysis were conducted using SPSS Statistics 22 (SPSS Inc., Chicago, IL, USA). Significance level was set at $p<0.05$.

To determine which kinematic parameters are related to the difference in VILR between the Atypical IRFCs and the other IFCPs, we first calculated Pearson correlation coefficients (r) between VILR and the kinematic variables that significantly differed between the Atypical IRFC and the other IFCPs. Second, the kinematic variables that significantly correlated with VILR were used to construct a multiple linear regression model with a stepwise forward method with VILR as dependent variable. These analysis were done for the Atypical and Typical IRFC subgroup and for the Atypical IRFC and IMFC subgroup. These analysis were not done for the entire subject group as we know that Typical IRFC and IMFC use opposing ankle strategies to reduce impact, which would obstruct linear modelling. Moreover, Typical IRFC and IMFC showed no significant difference in VILR (5), the dependent variable of these analysis.

RESULTS

A/ KINEMATIC DIFFERENCES

1. Spatiotemporal

We found that the Typical IRFC had longer contact times (0.254 ± 0.016 s) than the two other IFCP groups (Atypical IRFC: 0.240 ± 0.016 s, p= 0.05, CI: 0.000-0.028; IMFC: 0.238 ± 0.016 s, p= 0.024, CI: 0.002-0.030) and shorter flight times (0.112 ± 0.019 s) than the IMFC (0.134 ± 0.025, p= 0.021, CI: 0.003-0.040). No difference in flight time was found with Atypical IRFC (0.126 ± 0.022 s). No significant differences in step frequency (Typical IRFC: 2.72 ± 0.11 Hz; Atypical IRFC: 2.74 ± 0.18 Hz; IMFC: 2.73 ± 0.14 Hz) or step length (Typical IRFC: 1.20 ± 0.06 m; Atypical IRFC: 1.18 ± 0.08 m; IMFC: 1.19 ± 0.07 m) were found between the IFCP groups.

2. Sagittal plane

The observed significant differences in sagittal plane kinematic metrics between the different IFCPs are presented in table 2. The time series graphs for all sagittal plane joint and segment angles for the different IFCPS are shown in figure 1. For an overview of all sagittal plane kinematic metrics, also those not significantly differing between the different IFCPs, we refer to supplemental digital content 1 (SDC 1, table: overview of the sagittal plane kinematic metrics for the different initial foot contact patterns).

Table 2: *Sagittal plane kinematics with significant differences between the different IFCPs. 95% confidence intervals (CI) and Cohen's d effect sizes (d) of differences are reported.*

	Typical IRFC (n=31)	**Atypical IRFC (n=11)**	**IMFC (n=10)**	***CI***	***d***
Thigh					
Time of maximal posterior thigh inclination (% contact) [b]	23.7 ± 5.2	18.7 ± 8.2	14.9 ± 8.4	*b: 2.90-14.70*	*b: 0.42*
Knee					
Time of maximum knee flexion (% contact) [a]	40.8 ± 4.5	35.8 ± 3.3	39.5 ± 3.1	*a: 1.43-8.44*	*a: 0.13*
Knee flexion range of motion (°) [a]	29.9 ± 4.1	25.5 ± 3.4	26.7 ± 4.0	*a: 0.97-7.84*	*a: 0.16*
Shank					
Shank posterior inclination at initial contact (°) [a,b]	6.0 ± 3.1	2.7 ± 2.2	3.3 ± 2.8	*a: 0.86-5.89* *b: 0.09-5.30*	*a: 0.69* *b: 0.56*
Ankle					
Ankle angle at initial contact (°) [a,b,c]	7.2 ± 3.5	-3.1 ± 4.4	-10.4 ± 6.3	*a: 6.55-14.13* *b: 13.73-21.78* *c: 2.60-12.03*	*a: 6.44* *b: 11.00* *c: 4.56*
Initial ankle plantar flexion range of motion (°) [a,b]	6.7 ± 1.9	0.9 ± 0.9	0.1 ± 0.3	*a: 4.45-7.15* *b: 5.23-8.03*	*a: 1.35* *b: 1.53*
Time of maximum ankle dorsiflexion (% contact) [a,b]	52.7 ± 5.1	47.9 ± 4.2	47.9 ± 2.9	*a: 0.83-8.78* *b: 0.67-8.91*	*a: 0.09* *b: 0.09*
Ankle dorsiflexion range of motion (°) [a,b,c]	17.3 ± 2.8	21.3 ± 4.8	25.4 ± 4.5	*a: 0.73-7.09* *b: 4.73-11.31* *c: 0.15-8.06*	*a: 0.20* *b: 0.41* *c: 0.21*
Rearfoot					
Rearfoot angle at initial contact (°) [a,b,c]	20.4 ± 4.8	7.0 ± 5.1	1.6 ± 3.1	*a: 9.44-17.46* *b: 14.70-23.00* *c: 0.41-10.40*	*a: 0.96* *b: 1.35* *c: 0.39*
Vertical heel touchdown velocity ($m \cdot s^{-1}$) [a,b]	-1.18 ± 0.11	-1.08 ± 0.12	-0.97 ± 0.14	*a: 0.01-0.21* *b: 0.11-0.32*	*a: 0.09* *b: 0.19*

[a] *significant difference between Typical IRFC and Atypical IRFC. p<0.05*
[b] *significant difference between Typical IRFC and IMFC. p<0.05*
[c] *significant difference between IMFC and Atypical IRFC. p<0.05*

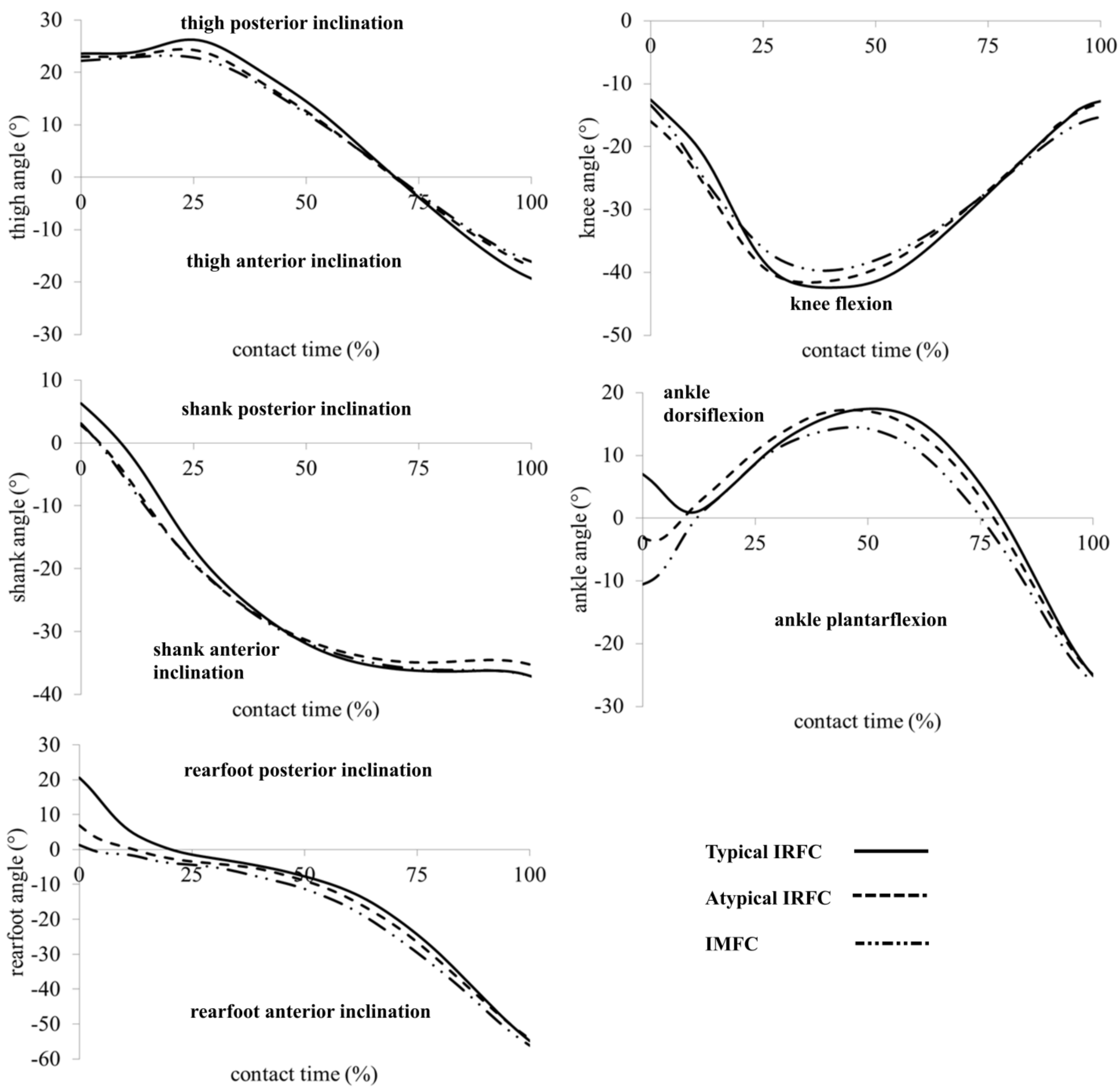

Figure 1: *Mean sagittal plane thigh, knee, shank, ankle and rearfoot kinematics for the different IFCP groups. The solid lines represent the Typical IRFC, The dashed lines the Atypical IRFC and the dash-dot-dot lines the IMFC. For the knee, ankle and rearfoot angle a zero value represents the standing position.*

Compared to our IFCP determination method, the kinematic method had a specificity of 100% and a sensitivity of 76% for the Typical IRFC. That is, all Typical IRFC indeed had an initial foot-to-ground angle greater than 8°. However, also 24% had initial foot-to-ground angles greater than 8° but were not defined as Typical IRFC using our method. For the IMFC the kinematic method had a sensitivity of 90% and a specificity of 83%. That is, 10% of the IMFC according to our method were not determined as IMFC with the kinematic method. Also 17% of the non-IMFC participants, according to our method, were kinematically determined as IMFC. From the group of Atypical IRFC 64% would have been kinematically determined as IMFC and 36% as IRFC.

3. Frontal plane ankle and rearfoot

The observed significant differences in frontal plane rearfoot and ankle kinematic metrics between the different IFCPs are presented in table 3. The time series graphs for frontal plane ankle joint and rearfoot segment angles for the different IFCPS are shown in figure 2. For an overview of all sagittal plane kinematic metrics, also those not significantly differing between the different IFCPs, we refer to supplemental digital content 2 (SDC 2, table: overview of the frontal plane kinematic metrics for the different initial foot contact patterns).

Table 3: *Frontal plane ankle and rearfoot kinematics with significant differences between the different IFCPS. 95% confidence intervals (CI) and Cohen's d effect sizes (d) of differences are reported.*

	Typical IRFC (n=31)	Atypical IRFC (n=11)	IMFC (n=10)	*CI*	*d*
Rearfoot					
Rearfoot inversion at initial contact (°) [a,b]	-9.5 ± 3.1	-15.0 ± 4.0	-17.5 ± 6.5	*[a]: 1.85-9.00* *[b]: 4.23-11.65*	*[a]: 0.45* *[b]: 0.66*
Time of maximal rearfoot eversion (% contact) [a,b]	42.0 ± 11.5	30.2 ± 10.0	28.7 ± 10.4	*[a]: 2.29-21.42* *[b]: 3.41-23.2*	*[a]: 0.32* *[b]: 0.36*
Rearfoot eversion range of motion (°) [a,b]	12.0 ± 3.0	16.4 ± 3.2	19.0 ± 4.7	*[a]: 1.41-7.38* *[b]: 3.96-10.14*	*[a]: 0.31* *[b]: 0.49*
Ankle					
Ankle inversion at initial contact (°) [b]	-6.4 ± 3.6	-9.2 ± 3.8	-10.9 ± 5.2	*[b]: 0.91-8.11*	*[b]: 0.57*
Time of maximum ankle eversion (% contact) [a,b]	41.5 ± 8.3	31.2 ± 10.8	29.3 ± 11.4	*[a]: 2.03-18.6* *[b]: 3.61-20.74*	*[a]: 0.28* *[b]: 0.33*
Ankle eversion range of motion (°) [b]	15.8 ± 3.5	18.9 ± 3.7	20.6 ± 4.6	*[b]: 1.44-8.30*	*[b]: 0.28*

[a] significant difference between Typical IRFC and Atypical IRFC. $p<0.05$
[b] significant difference between Typical IRFC and IMFC. $p<0.05$
[c] significant difference between IMFC and Atypical IRFC. $p<0.05$

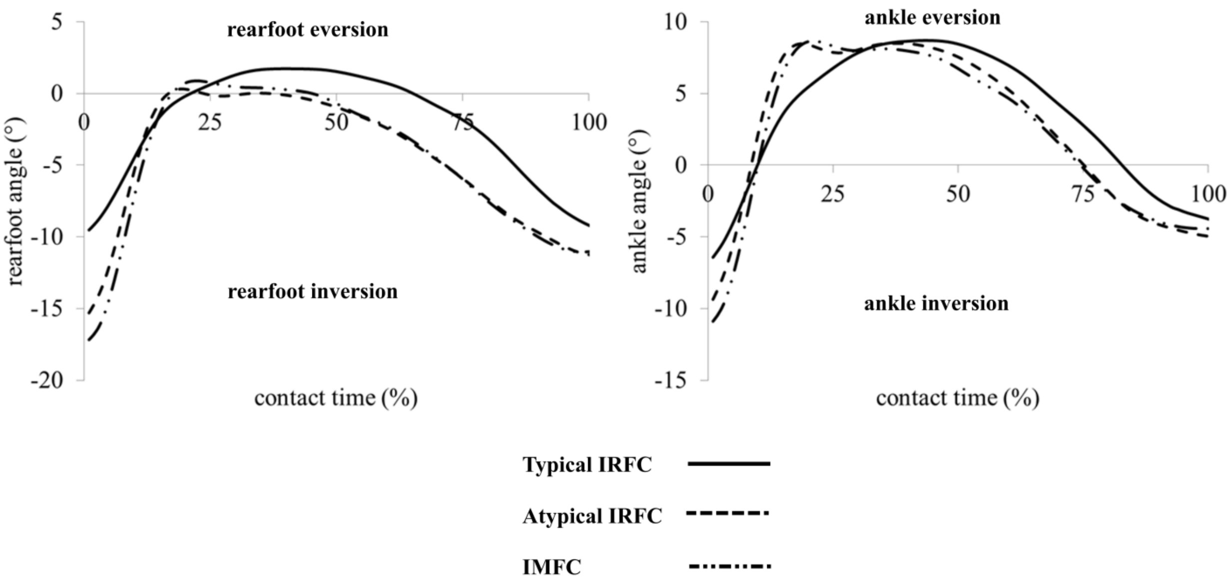

Figure 2: *Mean frontal plane rearfoot and ankle kinematics for the different IFCP groups. The solid lines represent the Typical IRFC, The dashed lines the Atypical IRFC and the dash-dot-dot lines the IMFC. A zero value represents the standing position.*

4. Spring mass model characteristics

Spring mass related characteristics for the different IFCPs are shown in table 4. Significant differences in spring mass model characteristics were found between the Typical IRFC and the other IFCPs. No significant differences in spring mass model characteristics were found between the Atypical IRFC and the IMFC.

Table 4: *Spring mass model related characteristics for the different IFCPs. Statistical differences between the different IFCPs and 95% confidence intervals (CI) and Cohen's d effect sizes (d) of differences are reported.*

	Typical IRFC (n=31)	**Atypical IRFC (n=11)**	**IMFC (n=10)**	***CI***	***d***
Maximal vertical GRF (N) [a]	1657 ± 216	1857 ± 139	1749 ± 125	*[a]: 36.4-363.2*	*[a]: 0.12*
Maximal vertical GRF (BW)	2.48 ± 0.20	2.65 ± 0.18	2.64 ± 0.22		
Vertical oscillation during contact (m)	0.080 ± 0.010	0.081 ± 0.009	0.078 ± 0.008		
K_{vert} ($kN \cdot m^{-1}$)	20.9 ± 2.7	23.3 ± 3.2	22.6 ± 3.1		
Leg compression during contact (m) [b]	0.151 ± 0.022	0.138 ± 0.016	0.128 ± 0.012	*[b]: 0.01-0.04*	*[b]: 0.16*
K_{leg} ($kN \cdot m^{-1}$) [a,b]	11.1 ± 1.9	13.6 ± 1.7	13.7 ± 1.6	*[a]: 838.1-4005.4*	*[a]: 0.21*
				[b]: 945.0-4227.1	*[b]: 0.21*
Knee stiffness (k_{knee}) ($N \cdot m \cdot ^{\circ -1} \cdot kg^{-1}$) [a,b]	0.096 ± 0.017	0.132 ± 0.022	0.116 ± 0.016	*[a]: 0.02-0.05*	*[a]: 0.33*
				[b]: 0.00-0.04	*[b]: 0.19*
Ankle stiffness (k_{ankle}) ($N \cdot m \cdot ^{\circ -1} \cdot kg^{-1}$) [a,b]	0.155 ± 0.031	0.128 ± 0.029	0.121 ± 0.032	*[a]: 0.00-0.05*	*[a]: 0.19*
				[b]: 0.01-0.06	*[b]: 0.24*
Posterior leg inclination at initial contact (°) [a,b]	22.0 ± 2.3	19.4 ± 1.4	18.3 ± 0.9	*[a]: 0.88-4.22*	*[a]: 0.13*
				[b]: 1.95-5.42	*[b]: 0.18*

[a] significant difference between Typical IRFC and Atypical IRFC. p<0.05
[b] significant difference between Typical IRFC and IMFC. p<0.05
[c] significant difference between IMFC and Atypical IRFC. p<0.05

B/ VILR IN THE DIFFERENT IFCP GROUPS

As already known from our previous study (5), we found a higher VILR in the Atypical IRFC (149.8 ± 26.6 BW/s) when compared with the Typical IRFC (115.2 ± 33.1 BW/s, p= 0.009, CI: 7.07-62.20) and the IMFC (97.6 ± 32.0 BW/s, p= 0.001, CI: 17.97-86.62). No significant difference in VILR was found between the Typical IRFC and the IMFC. The instant of VILR occurred earlier in the Atypical IRFC (0.014 ± 0.004 s, p<0.001, CI: 0.003-0.010) and IMFC (0.014 ± 0.007 s, p<0.001, CI:0.003-0.010) when compared with the Typical IRFC (0.021 ± 0.003 s). (Figure 3)

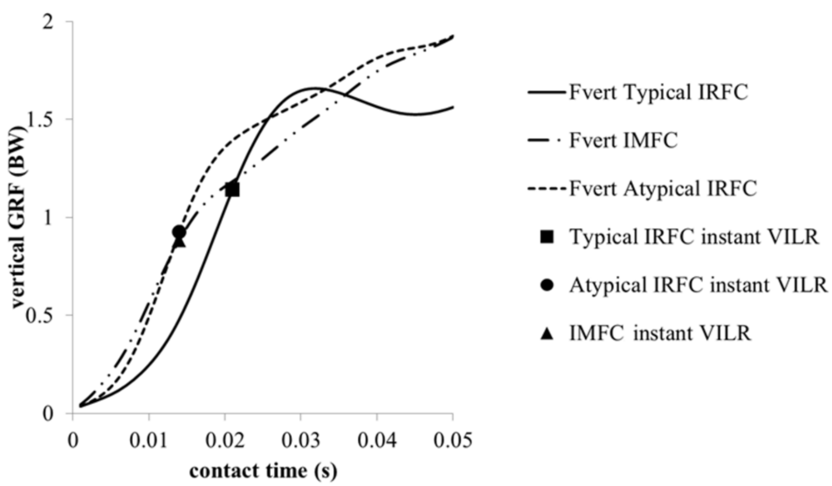

Figure 3: *Vertical GRF during the first 0.050 s of foot contact for the different IFCP with indication of instant of VILR.*

C/ KINEMATIC DIFFERENCES BETWEEN THE TYPICAL AND ATYPICAL IRFC TO PREDICT VILR

Table 5 displays the Pearson correlation coefficient between VILR and the kinematic variables that were found to differ between the two IRFC groups. We found the highest correlation with VILR for rearfoot posterior inclination at initial contact (~foot-to-ground angle) (RF_sag_IC).

Table 5: Pearson correlation coefficients (r) and p-values of correlations between VILR and selected global and distal parameters for the two IRFC groups.

'Global running style' parameters	**r**	**p**
Contact time (CT)	-0.628	<0.001
Knee flexion range of motion (knee_flex_ROM)	-0.621	<0.001
Ankle dorsiflexion range of motion	0.217	0.167
Fmax	0.365	0.018
k_{leg}	0.588	<0.001
k_{knee}	0.579	<0.001
k_{ankle}	0.115	0.418
Leg Angle at initial contact	-0.641	<0.001
'Distal' parameters	**r**	**p**
Shank posterior inclination at initial contact	-0.656	<0.001
Ankle sagittal plane angle at initial contact	-0.524	<0.001
Initial ankle plantar flexion range of motion	-0.559	<0.001
Rearfoot sagittal plane inclination at initial contact (RF_sag_IC)	-0.676	<0.001
Rearfoot frontal plane inversion at initial contact	-0.186	0.238
Rearfoot frontal plane eversion range of motion	0.179	0.257
v_{TDheel}	-0.040	0.802

The kinematic variables that were found to differ between Atypical IRFC and Typical IRFC and had a significant correlation with VILR were used to build a linear regression model to predict VILR in the IRFC group. The resulting model with the highest predictive value was able to predict VILR with an adjusted R^2 of 0.529 ($p<0.001$) using contact time (CT) and rearfoot posterior inclination at initial contact (RF_sag_IC) as predicting variables, indicating that longer contact times and more posteriorly inclined rearfoot angles are related to lower VILRs. (Table 6)

Table 6: *Results of stepwise multiple linear regression for VILR in the IRFC group. Unstandardized coefficients (B), standardized coefficients (β) and 95% confidence intervals for B (CI) are reported.*

Model	**B**	**β**	**p**	**CI**
Constant	350.39		<0.001	226.29-474.49
RF_sag_IC	-2.15	-0.475	0.001	-3.33 - -0.98
CT	-757.023	-0.368	0.007	-1290.07 - -223.98

D/ KINEMATIC DIFFERENCES BETWEEN THE ATYPICAL IRFC AND IMFC TO PREDICT VILR

Although we found less substantial kinematic differences between Atypical IRFC and IMFC than between the Atypical IRFC and Typical IRFC, the VILR was significantly higher in the Atypical IRFC compared to the IMFC. Table 7 shows the Pearson correlation coefficients between VILR and all the kinematic variables that were shown to differ between Atypical IRFC and IMFC.

Table 7: *Pearson correlation coefficients (r) and p-values of correlations between VILR and selected kinematic parameters for the Atypical IRFC and IMFC.*

'Global running style' parameters	**r**	**p**
Ankle dorsiflexion range of motion	-0.371	0.098
'Distal' parameters	**r**	**p**
Ankle sagittal plane angle at initial contact (Ankle_sag_IC)	0.594	0.004
Rearfoot sagittal plane inclination at initial contact	0.259	0.258

The kinematic variables that were found to be different between Atypical IRFC and IMFC and had a significant correlation with VILR were used to build a linear regression model to predict VILR. The final model was able to predict VILR with an adjusted R^2 of 0.319 (p=0.004) using the sagittal plane ankle angle at initial contact (Ankle_sag_IC) as predicting variable, indicating that a more plantar flexed ankle at initial contact is related to a lower VILR. (Table 8)

Table 8: *Results of stepwise multiple linear regression for VILR in the Atypical IRFC and IMFC group. Unstandardized coefficients (B) , standardized coefficients (β) and 95% confidence intervals for B (CI) are reported.*

Model	**B**	**β**	**p**	**CI**
Constant	148.706		<0.001	127.36-170.05
Ankle_sag_IC	3.6	0.594	0.004	1.26-5.94

DISCUSSION

Kinematic differences between IFCPs

When comparing global running style characteristics, Typical IRFC had longer contact times, shorter flight times, a less vertical leg angle at initial contact and a lower k_{leg} than both Atypical IRFC and IMFC. The Atypical IRFC and IMFC showed no differences in global running style characteristics, which confirms the hypothesis that the Atypical IRFC globally resemble more to an IMFC than to a Typical IRFC.

The main kinematic differences between IRFC and IMFC are found in the distal kinematics, more specific the ankle and foot angle at initial contact (2, 22, 25) which was confirmed in this study. In the Atypical IRFC participants, all but one showed a small initial ankle plantar flexion (~1.0°). The Atypical IRFC showed initial ankle and foot configurations that were in between the Typical IRFC and the IMFC. That is, a slightly plantar flexed ankle (~-3.1°) and a slightly posteriorly tilted foot (~7.0°). Using the kinematic method by Altman and Davis (2), based on the foot-to-ground angle at initial contact does not allow to discern the Atypical IRFC from the other IFCP. Moreover, When the strike index is measured with a force platform, COP position at the very initial foot contact is not reliable (24), and therefore a certain ground reaction force (GRF) threshold value is used (e.g. Williams and Cavanagh (26) used the COP position when the vertical GRF reached 10% of the maximal GRF) which could possibly classify Atypical IRFC as IMFC given the fast initial anterior COP movement in the Atypical IRFC. However, it is relevant to be able to discern these Atypical IRFC from Typical IRFC and IMFC as they showed the highest VILR which might be related to an increased risk for stress fracture injuries. To detect the Atypical IRFC patterns high frequent plantar pressure measurements are needed.

Relationship between kinematics and VILR

The second aim of this study was to investigate a relation between the observed kinematic differences and VILR, via correlations and multiple linear regressions. The observed correlations between kinematic parameters and VILR indicate that the Typical IRFC achieve lower VILR than the Atypical IRFC by the combination of a distal and a global running style strategy as we found that the constructed multiple linear regression model consisted of both distal (RF_sag_IC) and global running style parameters (CT and knee_flex_ROM). The rearfoot sagittal plane inclination at initial foot contact (RF_sag_IC) or ‘foot angle’ showed the highest correlation with VILR (r=-0.68) indicating that a more posteriorly inclined foot position or more pronounced IRFC corresponded with a lower VILR. On the other hand, we also found that parameters describing global running style such as contact time, knee flexion range of motion, k_{leg}, k_{knee}, leg angle at initial contact were significantly correlated with VILR, indicating that also the total body center of mass mechanics might influence the impact of running as measured with VILR. These findings confirm the statement of previous research by Bobbert, Schamhardt and Nigg (4) and more recently Clark *et al.* (7) that stated that the initial GRF is generated by a superimposition of both distal segment decelerations and the deceleration of the rest of the body.

In Typical IRFC, during the initial impact phase eccentric contraction of the tibialis anterior muscle during ankle plantar flexion absorbs part of the impact (12). This mechanism is possible due to the posteriorly inclined foot position and center of pressure position at the rear 1/3 of the foot, causing the GRF vector to be posteriorly directed from the ankle and/or subtalar joint and as such inducing an external ankle plantar flexion moment. The posteriorly tilted foot position at initial contact also allows a compression of the thick midsole structure under the heel part of the shoe and the heel fat pad itself (8, 28) which also cushion part of the impact. In IMFC, part of the impact is absorbed by eccentric contraction of the triceps surae muscles during initial ankle dorsiflexion. This mechanism is possible due to a COP position at the more anterior parts of the foot and a ‘flat’ or even slightly anteriorly inclined foot position at initial foot contact which result in the GRF vector being directed anterior to the subtalar and/or ankle joint inducing an external dorsiflexion moment. We hypothesize that in the Atypical IRFC, the higher VILR can be explained by the limited use of initial eccentric plantar flexion and the cushioning properties of the heel part of the shoe to absorb the impact, due to the slightly posteriorly inclined foot position at initial contact and fast anterior movement of the COP. The initial position at the rear 1/3 of the foot and fast anterior movement of the COP into the midfoot zone causes the GRF to be directed more ‘through’ the ankle joint which limits both initial dorsiflexion or plantar flexion impact absorbing strategies. The common belief that pronounced ‘heel striking’ induces the greatest VILR should be reconsidered.

The negative correlation between the sagittal plane ankle (dorsi- (+) or plantar (-) flexion) and rearfoot (posterior (+) or anterior (-) inclination) angle at initial contact and VILR in the Typical and Atypical IRFC and the positive correlation in the Atypical IRFC and IMFC indicate that Typical IRFC and IMFC use opposite ankle strategies to reduce impact. In the Typical/Atypical IRFC group a more pronounced dorsiflexed ankle (+) at initial contact relates to a decreased VILR (~negative correlation), while in the Atypical/IMFC group a more pronounced plantar flexed ankle (-) at initial contact relates to a decreased VILR (~positive correlation).

A possible limitation of this study lies in its design. As this study aimed at assessing between-subject differences, the observed correlations between running kinematics and VILR are limited to the range of running styles of our subject group. For instance, Hobara *et al.* (14) found that, using a within-subject approach, runners were able to maximally reduce VILR with a step frequency increase of 17.5%. In our study, no difference in step frequency was found between the IFCP groups and consequently no relationship with VILR was found. To be able to demonstrate that step frequency adjustments could indeed be a possible strategy to reduce VILR, a within-subject design would be better suited. In other words, a combined study design assessing both between-subject kinematic and VILR differences when running with habitual running style, and also the within-subject effect of selected instructed running style adaptations on VILR should provide more profound insights in the relationship between running style and VILR.

Conclusions

Typical IRFC, Atypical IRFC and IMFC are considerably different running styles with differences in kinematics and VILR. The observed relationships between running kinematics and VILR showed that the different IFCPs use different impact reducing kinematic strategies. The observed higher VILR in the Atypical IRFC could be explained by both global running style (shorter contact times and greater k_{leg}) and distal ankle and foot kinematics (flatter foot at initial foot contact followed by a limited ankle plantar flexion) that indicate a limited use of known kinematic impact reducing ‘strategies’ such as initial ankle plantar flexion in Typical IRFC and initial ankle dorsiflexion in IMFC.

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Conflict of interest

The authors have no conflicts of interest.

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SUPPLEMENTAL DIGITAL ONLINE CONTENT

SDC1: Sagittal plane kinematic metrics for the different IFCPs.

	Typical IRFC (n=31)	Atypical IRFC (n=11)	IMFC (n=10)
Thigh			
Thigh angle at initial contact (°)	24.0 ± 3.7	22.5 ± 4.4	22.1 ± 2.0
Thigh angle at take-off (°)	-19.2 ± 3.3	-17.4 ± 4.1	-16.2 ± 3.0
Maximum posteriorly inclined thigh angle (°)	26.7 ± 3.9	24.1 ± 4.7	23.7 ± 2.0
Time of maximal posterior thigh inclination (% contact) [b]	23.7 ± 5.2	18.7 ± 8.2	14.9 ± 8.4
Knee			
Knee angle at initial contact (°)	-13.0 ± 5.0	-15.7 ± 5.1	-13.5 ± 5.3
Knee angle at take-off (°)	-12.8 ± 5.5	-12.9 ± 3.9	-15.6 ± 4.5
Maximum knee flexion (°)	-42.9 ± 5.1	-41.2 ± 6.9	-40.2 ± 4.7
Time of maximum knee flexion (% contact) [a]	40.8 ± 4.5	35.8 ± 3.3	39.5 ± 3.1
Knee flexion range of motion (°) [a]	29.9 ± 4.1	25.5 ± 3.4	26.7 ± 4.0
Shank			
Shank posterior inclination at initial contact (°) [a,b]	6.0 ± 3.1	2.7 ± 2.2	3.3 ± 2.8
Ankle			
Ankle angle at initial contact (°) [a,b,c]	7.2 ± 3.5	-3.1 ± 4.4	-10.4 ± 6.3
Initial ankle plantar flexion range of motion (°) [a,b]	6.7 ± 1.9	0.9 ± 0.9	0.1 ± 0.3
Maximum ankle dorsiflexion (°)	17.5 ± 4.4	17.2 ± 4.6	14.8 ± 4.2
Time of maximum ankle dorsiflexion (% contact) [a,b]	52.7 ± 5.1	47.9 ± 4.2	47.9 ± 2.9
Ankle dorsiflexion range of motion (°) [a,b,c]	17.3 ± 2.8	21.3 ± 4.8	25.4 ± 4.5
Rearfoot			
Rearfoot angle at initial contact (°) [a,b,c]	20.4 ± 4.8	7.0 ± 5.1	1.6 ± 3.1
Vertical heel touchdown velocity ($m \cdot s^{-1}$) [a,b]	-1.18 ± 0.11	-1.08 ± 0.12	-0.97 ± 0.14

[a] significant difference between Typical IRFC and Atypical IRFC. $p<0.05$

[b] significant difference between Typical IRFC and IMFC. $p<0.05$

[c] significant difference between IMFC and Atypical IRFC. $p<0.05$

SUPPLEMENTAL DIGITAL CONTENT 2

SDC 2: Frontal plane ankle and rearfoot kinematic metrics for the different IFCPs.

	Typical IRFC (n=31)	Atypical IRFC (n=11)	IMFC (n=10)
Rearfoot			
Rearfoot inversion at initial contact (°)[a,b]	-9.5 ± 3.1	-15.0 ± 4.0	-17.5 ± 6.5
Maximal rearfoot eversion (°)	2.5 ± 2.3	1.4 ± 2.4	1.6 ± 2.3
Time of maximal rearfoot eversion (% contact) [a,b]	42.0 ± 11.5	30.2 ± 10.0	28.7 ± 10.4
Rearfoot eversion range of motion (°) [a,b]	12.0 ± 3.0	16.4 ± 3.2	19.0 ± 4.7
Ankle			
Ankle inversion at initial contact (°) [b]	-6.4 ± 3.6	-9.2 ± 3.8	-10.9 ± 5.2
Maximum ankle eversion (°)	9.4 ± 3.2	9.7 ± 3.2	9.7 ± 1.7
Time of maximum ankle eversion (% contact) [a,b]	41.5 ± 8.3	31.2 ± 10.8	29.3 ± 11.4
Ankle eversion range of motion (°) [b]	15.8 ± 3.5	18.9 ± 3.7	20.6 ± 4.6

[a] significant difference between Typical IRFC and Atypical IRFC. $p<0.05$

[b] significant difference between Typical IRFC and IMFC. $p<0.05$

[c] significant difference between IMFC and Atypical IRFC. $p<0.05$

STUDY 3

Magnitude and spatial distribution of impact intensity under the foot relates to initial foot contact pattern

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ABSTRACT

Initial foot contact patterns (IFCPs) (initial rear- (IRFC), mid- (IMFC) or forefoot contact (IFFC)) are related to impact intensity and initial ankle and foot kinematics. Hence, we hypothesize that impact intensity and its spatial distribution under the foot will differ between different IFCPs. Forty-nine subjects ran at 3.2 $m \cdot s^{-1}$ over an indoor running track while ground reaction forces (GRF) and shoe-surface pressures were recorded. Also IFCP was determined. A four-zone footmask was applied to assess the spatial distribution of the vertical GRF (VGRF) under the foot. We calculated peak vertical instantaneous loading rate of the GRF (VILR)(per foot zone). A spectral decomposition of the VGRF into a low (LO)(non-impact, ≤10 Hz) and high frequency (HI)(impact, >11Hz) component was done. Both VILR and HI-VGRF peak were used as impact intensity measures. IMFCs were shown to have the lowest and Atypical IRFCs the highest impact intensity. The impact intensity was mainly situated under the rear- and midfoot for the Typical IRFC, under the midfoot for the Atypical IRFC and under the mid- and forefoot for the IMFC. These findings indicate that for passive impact reduction different IFCPs would benefit from cushioning in different zones of the shoe.

INTRODUCTION

Glossary of terms

IFCP	initial foot contact pattern
IRFC	initial rearfoot contact pattern
IFMC	initial midfoot contact pattern
IFFC	initial forefoot contact pattern
VILR	peak vertical instantaneous loading rate of the ground reaction force
GRF	ground reaction force
VGRF	vertical ground reaction force
HI-VGRF	the high frequency component of the vertical ground reaction force

The classification of initial foot contact patterns (IFCP), defining rearfoot (IRFC), midfoot (IMFC) or forefoot contact patterns (IFFC), has proven relevant due to a possible relation between IFCP and running economy or performance (21), but it is primarily relevant because of its relationship with the intensity of ground reaction force (GRF) during the initial impact phase. We know that different IFCPs are characterized by differences in peak vertical instantaneous loading rate of the ground reaction force (VILR) (5, 6), and as such may represent possible differences in stress fracture injury susceptibility (18, 26). The relation between IFCP and impact intensity can be explained by the fact that IFCP determines the contributions of impact reducing mechanisms. Such mechanisms are initial ankle plantar flexion when running with an IRFC (13) or initial ankle dorsiflexion when running with an initial IMFC or IFFC (17), but also the amount of passive cushioning by different parts of the shoe sole or heel fat pad during impact (11) (Breine *et al. Submitted*).

When assessing the impact intensity of a running foot contact often VILR is used (5, 6, 18, 24, 26). Also the spectral decomposition of the vertical GRF (VGRF) signal into a low frequency or active component, and a high frequency or impact component allows to separate the impact characteristics of the VGRF from the rest of the curve, and as such determine the impact intensity of a running foot contact (12, 24). Until now, the difference in impact intensity between different IFCPs has mainly been assessed by comparing the loading rate of the VGRF (5, 6) and not by conducting a spectral decomposition of the VGRF signals. Shorten *et al.* (24) have shown through spectral decomposition of the VGRF signal that the total VGRF impact peak, often referred to as 'heel impact peak', might not be a reliable measure to assess impact intensity as this peak consists of both a high frequency (~impact) and low frequency (~non-impact) component. A spectral decomposition of the VGRF in runners with different IFCPs should allow us to determine and compare impact intensity between different IFCPs, by calculating the peak magnitude of the high frequency component of the VGRF (HI-VGRF peak).

As IFCP influences the consecutive foot and ankle motion (23) and is related to impact intensity (5, 6) we hypothesize that IFCP will also influence the spatial distribution of the VGRF impact intensity over different foot zones (e.g. rear-, mid- and forefoot). Assessing the spatial distribution of the impact intensity could allow us to identify, for different IFCPs, which foot zones experience the highest 'impact loading' and could provide useful indications for optimization of passive cushioning in running footwear, specific for different IFCPs.

Therefore, the first aim of this study is to compare the impact intensity, as measured by both VILR and HI-VGRF peak during the initial impact phase between runners with different IFCPs. In the present study we defined the initial impact phase as the first 0.050s of foot contact. This timeframe was based on the fact that impact forces in running reach their peak earlier than 0.050s after initial contact (20, 24). Moreover, Shorten *et al.* (24) defined high frequent impact signals with frequencies above 10 Hz, that as such show a half oscillation time of 0.050s or shorter. We hypothesize that runners with different IFCPs will show differences in VILR and HI-VGRF peak. Secondly this study aims to compare the spatial distribution of the impact intensity over different foot zones (rear-, mid- and forefoot) between different IFCPs. Impact intensity per foot zone will be measured by calculating the local VILR and the local HI-VGRF peak. We hypothesize that the impact intensity (under each foot zone) will differ between the different IFCP groups. Therefore, we tested the null hypothesis of equal VILR and HI-VGRF peak for the different IFCP groups. We tested the null hypotheses of a) equal rearfoot VILR in different IFCP groups and b) equal midfoot and forefoot VILR in different IFCP groups. We also tested the null hypotheses of a) equal rearfoot HI-VGRF peak in different IFCP groups and b) equal midfoot and forefoot HI-VGRF peak in different IFCP groups. We also hypothesize that within each IFCP group a different foot zone will have the greatest impact intensity. Therefore, we tested the null hypothesis of equal VILR and HI-VGRF peak in the different foot zones, within each IFCP group.

METHODS

Subjects

For the present study we used the same dataset as in a previous study (6), except for 5 subjects who were not retained due to a manufacturer software bug which prevented data exporting for these subjects. Forty-nine subjects were retained in the present study (37 men and 12 women). For the male subjects mean ± SD age was 28.6 yrs. ± 8.4; body mass 72.2 kg ± 5.8; height 1.80 m ± 0.05. For the female subjects mean ± SD age was 27.8 yrs. ± 8.2; body mass 58.6 kg ± 4.6; height 1.67 m ± 0.05. For a more detailed description of the subjects and complete experimental protocol we refer to our previous study (6). The present study was approved by the ethical committee of the Ghent University hospital and written informed consent was obtained prior to participation. Methods that were also used in our previous study are shortly described below. Methods specific for the present study are described in more detail.

Protocol

We recorded GRFs (1000 Hz, AMTI, Watertown, MA, USA) and shoe-surface pressures (500 Hz, Footscan, RSscan International, Olen, Belgium) of three left foot running contacts at 3.2 $m \cdot s^{-1}$. Subjects all wore the same shoes (Li Ning Magne (ARHF041)). Shoes were modified for optimizing shoe-surface pressure measurements by substituting a flat outsole and filling in the midfoot region of the midsole with an EVA foam, so as to remove the cavity between the heel and forefoot part of the shoe. For a more detailed description of the experimental shoe we refer to our previous study (6). Measured GRFs were instantly imported and synchronized in the Footscan 7 software for a dynamic calibration of the shoe-surface pressures. We used the 500 Hz synchronized GRF data for all further calculations. GRF data were filtered with a Butterworth 2nd order low pass filter with a cut-off frequency of 80 Hz. For the present study we focused on the initial impact phase of foot contact which we defined as the first 0.050s of foot contact.

Data analysis

We used the shoe-surface pressure distribution to determine the VGRF transmitted through the different regions of the foot. In the Footscan 7 software we applied a 4-zone mask : (1) medial and (2) lateral rearfoot (splitting the posterior 1/3 of the foot across the midline), (3) midfoot (middle 1/3 of the foot) and (4) forefoot zone (distal 1/3 of the foot). As such, the VGRF could be divided into spatial components. The VILRs (per foot zone) were calculated as the first derivative of the VGRF (per foot zone) over a 0.004 s interval, as a first measure of impact intensity. VILRs were normalized to subjects' bodyweight (BW).

With a half-wave fast Fourier transform analysis (without any additional windowing, zero padding or detrending processing) both the total VGRF signal and the VGRF signals per foot zone were transformed into the frequency domain. For these analysis we considered all non-zero data from the entire stance phase. With an inverse fast Fourier transform analysis the data with frequency content up to 10 Hz was recomposed into the time domain as the low frequency VGRF. The high frequency VGRF content was determined by subtracting the low frequency content from the original VGRF signal. As such the VGRF signals (per foot zone) were decomposed into a high frequency (HI) (~impact, >11 Hz) and low frequency component (LO) (~non-impact, ≤10 Hz). For both the total VGRF and the VGRF signals per foot zone, the peak value of the high frequency VGRF component (HI-VGRF peak), during the first 0.050s of contact, was determined as a second measure of impact intensity.

Each foot contact was categorized as a Typical IRFC, Atypical IRFC or IMFC. There was only one recorded IFFC trial, which was not retained for further analysis. This IFCP determination was done based on a combination of strike index (7), time of first metatarsal contact and a qualitative assessment of the COP pattern. This approach has been described in our previous research which was the first study to discern Typical and Atypical IRFCs (6). These Atypical IRFCs are characterized by an initial fast anterior COP movement along the lateral shoe margin into the midfoot zone of the foot, after which the COP moves medially into the midfoot zone, and an early first metatarsal contact. Whereas in the Typical IRFC the initial COP movement is slower and almost instantly moves towards the foot midline in the rearfoot zone. We used the IFCP classification into Typical IRFC, Atypical IRFC and IMFC for all statistical comparisons between-IFCP groups.

To provide a qualitative view of the average pressure build-up under the foot in the different IFCP groups during the initial impact phase, average pressure distribution images were constructed per IFCP group over 0.010s intervals for the first 0.050s of foot contact. These images were created with a spatial normalization method, using Matlab and Python routines, that allows averaging shoe-surface pressure images between subjects. These methods were developed and described by Pataky *et al.* (22).

Statistics

For statistical analysis, all derived variables of the three recorded trials were averaged per subject. If all three trials for each subject could not be assigned to the same IFCP group, the average value for statistical analysis was calculated based on the trials of the most frequent (i.e. two out of three trials) IFCP. ANOVAs with post-hoc pairwise analysis with Bonferroni correction were conducted to assess between-IFCP group differences (Typical IRFC vs. Atypical IRFC vs. IMFC). We assessed within-IFCP group differences between the different foot zones (rear- vs. mid- vs. forefoot) using repeated measures analysis with post-hoc pairwise analysis with Bonferroni correction. Pearson correlation coefficients (r) were calculated for the relation between the (local) impact intensity measures VILR and HI-VGRF peak. All statistical analysis were conducted using SPSS Statistics 22 (SPSS Inc., Chicago, IL, USA). Significance level was set at $p<0.05$.

RESULTS

We observed a significantly higher VILR in the Atypical IRFC (n=11) when compared with the Typical IRFC (n=29) and the IMFC (table 1). No difference in VILR was found between the Typical IRFC and IMFC. We found that the IMFC had a significantly lower HI-VGRF peak than the Typical and Atypical IRFC. No difference in HI-VGRF peak was found between the Typical and Atypical IRFC (table 1). The VGRF and its decomposition in HI-VGRF and LO-VGRF is shown in figure 1 for each IFCP group.

Table 1: Mean ± standard deviation of impact intensity measures VILR and HI-VGRF peak in the different IFCP groups.

	Typical IRFC (n=29)	Atypical IRFC (n=11)	IMFC (n=9)
VILR ($BW \cdot s^{-1}$)	110.2 ± 33.6	153.7 ± 32.6 *	103.2 ± 30.2
HI-VGRF peak (N)	355 ± 99	366 ± 82	198 ± 82 *

* significantly different from the other IFCP groups. p<0.05.

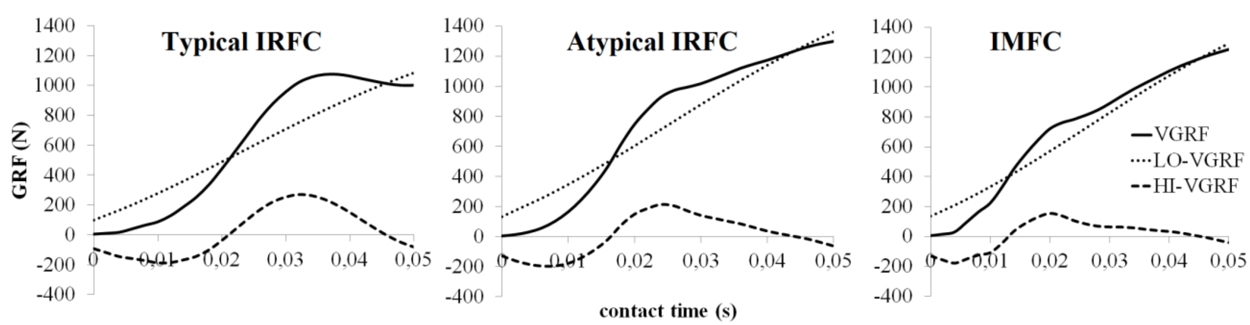

Figure 1: *Average curves of the spectral decomposition of VGRF into HI-VGRF (>10 Hz) and LO-VGRF (<10Hz) for the different IFCPs during the initial impact phase.*

The spatial distribution of the VGRF over the different foot zones during the initial impact phase is shown in figure 2.

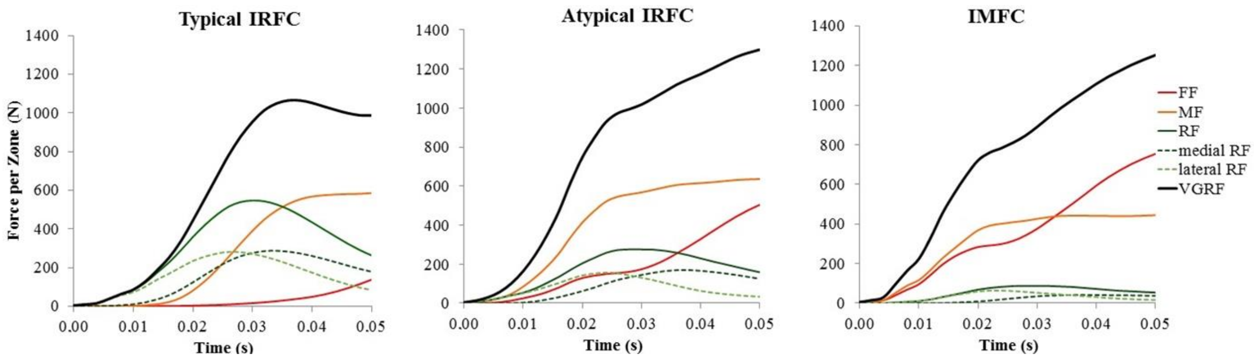

Figure 2: *Spatial distribution of the VGRF during the initial impact phase (first 0,050s of foot contact) over the lateral and medial rearfoot, midfoot and forefoot zone. Separate graphs are shown for the different IFCP (Typical IRFC, Atypical IRFC and IMFC).*

For the different foot zones we found significant impact intensity differences between the different IFCPs. In the rearfoot zone we found the highest rearfoot VILR and HI-VGRF peak in the Typical IRFC and the lowest rearfoot VILR and HI-VGRF peak in the IMFC. The Atypical IRFC showed rearfoot VILR and HI-VGRF peak in between the Typical IRFC and IMFC. In the midfoot zone we found that the Atypical IRFC had a higher VILR than the IMFC and that the IMFC had the lowest HI-VGRF peak. In the forefoot zone we found that the Typical IRFC had the lowest VILR and HI-VGRF peak. (Figure 3 and 4)

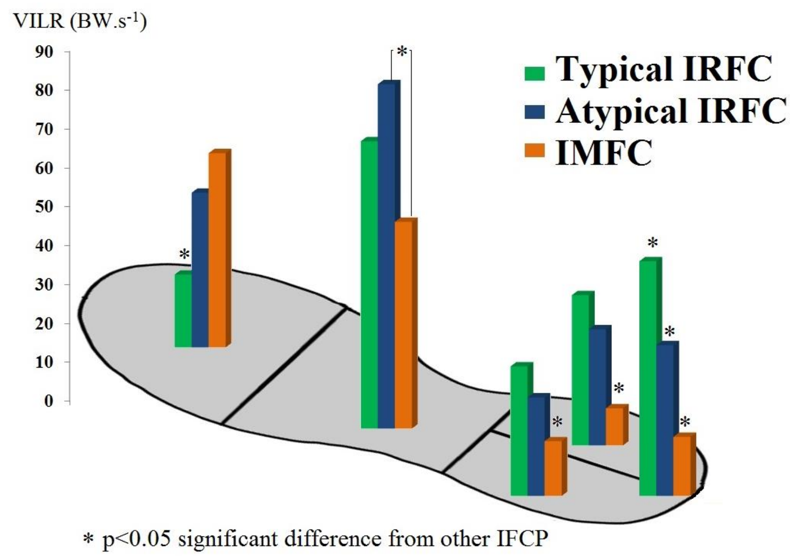

Figure 3: *VILR per foot zone for the different IFCPs. Depicted on a left foot footprint. At the rearfoot zone both the rearfoot lateral, medial and the merged rearfoot data are presented. Height of the bars should be interpreted relative to the scale*

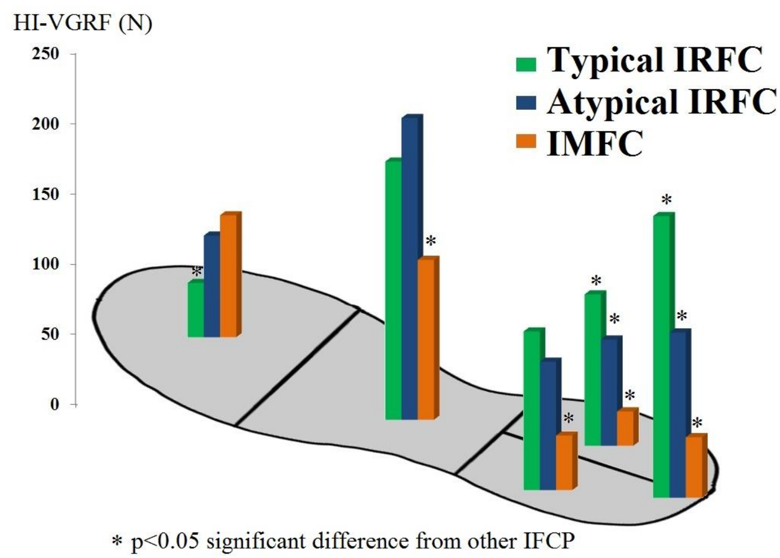

Figure 4: *HI-VGRF peak per foot zone for the different IFCPs. Depicted on a left foot footprint. At the rearfoot zone both the rearfoot lateral, medial and the merged rearfoot data are presented. Height of the bars should be interpreted relative to the scale*

We observed a different distribution of the impact intensity over the different foot zones within the different IFCPs. For the typical IRFC the greatest local VILR was situated under the rearfoot and midfoot zone. For the Atypical IRFC the greatest local VILR was situated under the midfoot zone. For the IMFC the greatest local VILR was situated under the midfoot and forefoot zone. For the Typical IRFC the HI-VGRF peak was the highest under the rearfoot and midfoot zone. For the Atypical IRFC the HI-VGRF peak was the greatest under the midfoot zone. For the IMFC/IFFC the HI-VGRF peak was the greatest under the midfoot and forefoot. (Figure 3 and 4)

For the entire subject group we found a significant positive correlation between the different impact intensity measures per foot zone VILR and HI-VGRF peak ranging from r 0.790 to 0.933 ($p<0.001$). This indicates that the different impact intensity measures are significantly related.

A qualitative view of the average pressure build-up under the foot in the different IFCP groups during the initial impact phase is given in Figure 5. On these images also a mask is depicted showing the lateral and medial rearfoot, midfoot and forefoot zone.

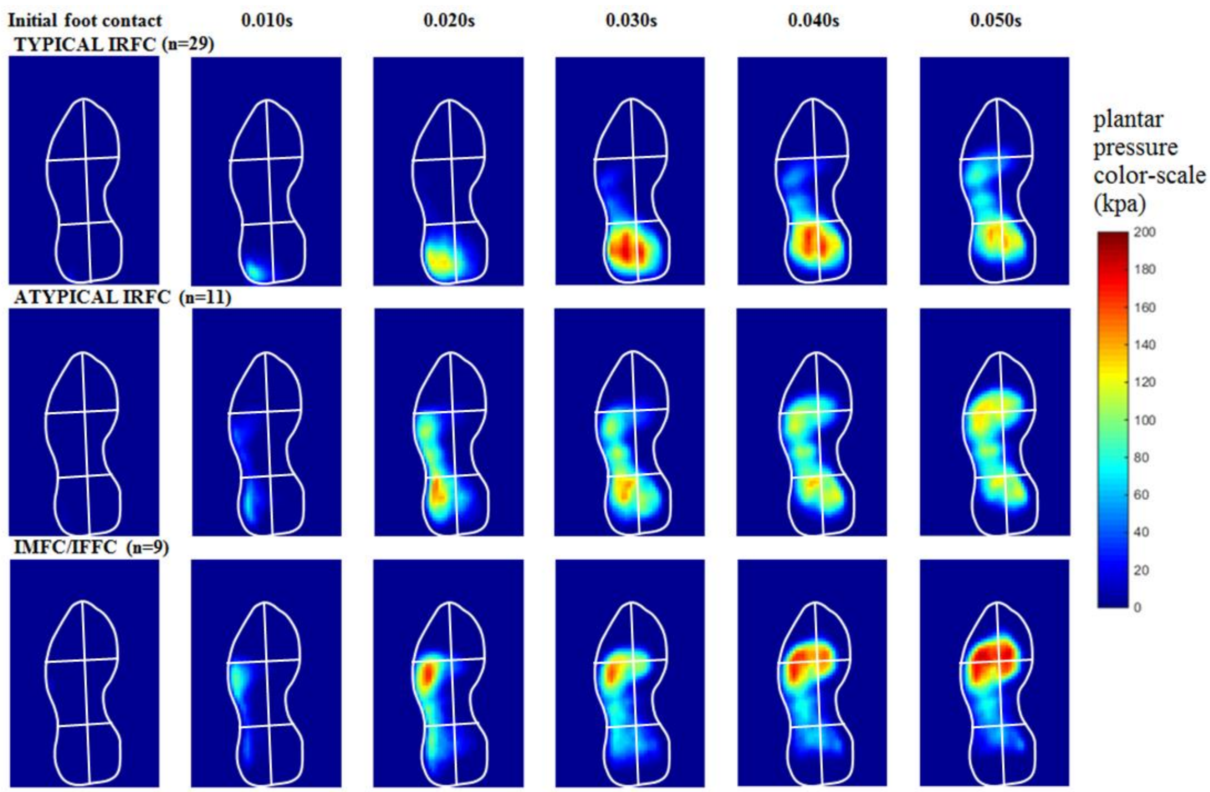

Figure 5: *Qualitative view of the average pressure build-up under the foot in the different IFCP groups during the initial impact phase over 0.010s intervals. A color-scale from 0-200 kPa indicates the shoe-surface pressure.*

DISCUSSION

The first purpose of this study was to compare the impact intensity during the initial impact phase between runners with different IFCPs. As hypothesized, the different IFCPs showed differences in impact intensity. Using the HI-VGRF peak as impact intensity measure the Typical and Atypical IRFC showed a higher impact intensity than the IMFC. Although Shorten et al. (24) have shown that this measure allows quantification of impact intensity and cushioning effects, to our knowledge, this is the first study to compare impact intensity between runners with different IFCPs using HI-VGRF peak as an impact intensity measure. The difference in impact intensity between the different IFCPs seems to be dependent on which measure is used, VILR or HI-VGRF peak. This can be explained by how the two different measures are calculated.

The spectral decomposition of the VGRF into a high frequency VGRF (>10 Hz, ~impact) and a low frequency VGRF (<10 Hz, non-impact) component allowed us to separate the high frequent impact characteristics of the VGRF from the rest of the GRF. However, as the VILR is calculated on the non-decomposed VGRF signal it describes both the low and high frequent component of the VGRF signal. As such, VILR is also influenced by the low frequent signal content, which is not the case for HI-VGRF peak. Regardless of which impact intensity measure was used, the Atypical IRFC showed the highest impact intensity, and the IMFC the lowest impact intensity.

A second purpose of this study was to compare the spatial distribution of the impact intensity under the foot between the different IFCPs. Both VILR and HI-VGRF peak showed similar results. As hypothesized, we found that in the Typical IRFC the greatest impact intensity was situated under the rearfoot and midfoot zone, for the IMFC under the midfoot and forefoot zone and for the Atypical IRFC under the midfoot zone. The 2D visualisation of the average pressure build-up under the foot in the different IFCP groups during the initial impact phase (fig. 5) also showed that in the Typical IRFC the greatest pressure build up is situated under the rearfoot, while for the IMFC under more anterior parts of the foot. The Atypical IRFC showed a pressure build up mainly under the midfoot zone. These findings indicate that the spatial distribution of the VGRF impact intensity under the foot indeed is related to IFCP.

The local force and impact intensity measures, measured at the different zones under the foot provide an indication of the loading that acts upon the shoe sole from the ground up. These loading measures per foot zone can be spatially further refined by examining the loading per pressure cell under the foot (fig. 5). In the rearfoot zone the force is located mainly under the heel, in the midfoot zone mainly at the lateral border and in the forefoot zone mainly under the estimated location of the metatarsals. However, the forces acting on the shoe sole, and its role in absorbing the impact intensity, are a combination of the forces acting upon the plantar surface and the forces acting upon the shoe sole from the inside of the shoe. The latter we don't know, but follow the anatomical supporting structures of the foot, which is largely reflected in the pressure measurements under the sole (fig. 5).

A limitation of this study is that all subjects wore the same shoes. We know that shoe characteristics can influence IFCP and VGRF characteristics (1, 8, 19) which means that the obtained results are specific to the shoe used in the present study. Future research using comparable methods could assess the influence of shoe characteristics on IFCP and spatial VGRF distribution. Also the cut-off frequency of 10 Hz distinguishing LO-VGRF and HI-VGRF and the foot zone definitions could affect the numerical results, but moderate variations in these premises would not change the observed relative differences in impact intensity between the different IFCPs or between the different foot zones.

Several studies have assessed the influence of foot strike on the plantar pressure and force distribution under the foot (2, 14, 15). These studies showed greater force-time integrals and peak forces under the rearfoot, measured using in-sole pressure sensors, in rearfoot strike runners when compared to midfoot or forefoot strike runners (2, 14, 15). However, these variables might be suited to assess general loading distribution differences, but are less useful to assess impact intensity differences between IFCPs. The total VGRF is constrained by the fact that the total vertical impulse of the VGRF equals that of gravity. Decomposing the VGRF signal into low frequency, non-impact, and high frequency, impact components allows for a better assessment of impact intensity characteristics and cushioning effects (24, 25).

Our analyses allow us to compare the *in vivo* loading under the shoe with the loading that is applied during *in vitro* mechanical impact testing of running shoes. Figure 2 shows that in the Typical IRFC the force generated under the rearfoot zone (green line) indeed experiences an impact loading that is comparable to gravity driven impact testing as performed on the heel part of running shoes (ASTM F1976-13, Standard Test Method for Impact Attenuation of Athletic Shoe Cushioning Systems and Materials, ASTM International, West Conshohocken, PA, 2013, www.astm.org), which show sinusoidal force pulses with peaks of about 750-1250 N and a half period time of about 0.030-0.040 s (24). This was less the case for the Atypical IRFC and the IMFC, where the heel part was less loaded.

The decomposition of the VGRF into HI- and LO-VGRF is analogous to a decomposition into the contribution of the support leg center of mass deceleration (~impact) and the contribution of the deceleration of the 'rest of the body' (~non-impact) to the total VGRF (3, 4). Previously, Bobbert *et al.* (3, 4) and more recently Clark *et al.* (10) stated that the initial GRF is indeed generated by a superimposition of both distal segment decelerations and the deceleration of the rest of the body and this superimposition results in the typical GRF pattern in Typical IRFC with an initial transient 'impact' peak. The Atypical IRFC were shown to have shorter contact times than the Typical IRFC (6) (Breine *et al.* submitted) indicating a faster deceleration of the 'rest of the body'. In other words, we hypothesize that the greater VILR in Atypical IRFC compared to Typical IRFC can be explained by a greater contribution of the deceleration of the 'rest of the body', while the greater VILR in the Atypical IRFC when compared to the IMFC can be explained by a greater deceleration of the stance leg (~HI-VGRF peak). We know that the mechanical 'proof' of how the differences in VGRF and impact intensity between different IFCPs are realised could be provided by calculation and summation of the separate segmental decelerations. However, we have not yet been able, nor to our knowledge have other researchers been able to conduct such an analysis.

The practical implications of the between-IFCP differences in impact intensity and impact intensity spatial distribution are that these findings indicate that runners with different IFCPs would benefit from passive shoe cushioning in different specific foot zones. However, shoe design and especially midsole thickness and heel-toe offset have been shown to influence IFCP (8, 9, 16) and, as this study showed, could also indirectly influence the spatial VRGF distribution. Future research should assess the influence of IFCP specific cushioning footwear design on impact intensity and IFCP. Shorten *et al.* (2011) have shown that passive cushioning mainly attenuates the HI-VGRF peak (24). However, VILR describes the impact intensity of the actual total loading that is experienced during the initial impact phase and has been shown to be related to stress fracture injury risk (18, 26). As such, it remains a valuable variable. Future research should assess both VILR and HI-VGRF peaks when assessing impact intensity. We hypothesize that impact intensity reduction could be achieved by passive cushioning in the rearfoot and midfoot zone for runners with a Typical IRFC, mainly in the midfoot zone for runners with an Atypical IRFC and in the midfoot and forefoot zone for runners with an IMFC.

The main finding of this study is that the impact intensity, as measured with VILR and HI-VGRF peak, and the spatial distribution of the impact intensity over the different foot zones are related to IFCP. In Typical IRFC the greatest impact intensity is generated under the rearfoot and midfoot zones, in Atypical IRFC under the midfoot zone and in IMFC under the midfoot and forefoot zones. This indicates that for optimization of passive shoe cushioning for impact intensity reduction the different IFCPs need cushioning in different zones of the shoe.

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DISCUSSION

1. MAIN RESEARCH FINDINGS

The present thesis aimed to answer several research questions regarding the determination of IFCPs, the influence of speed and the relation with impact intensity. A summary of our answers to these research questions is presented in the following section.

1.1. Can we accurately assess strike index (and IFCP) at initial foot contact during constant pace shod running?

In our first study, as hypothesized, **the use of a combined high frequent plantar pressure and force plate system allowed for an accurate determination of SI at initial foot contact**. The 2 m FootScan pressure plate made by RsScan, consists of small resistive sensors (0.5088 x 0.762 cm) (~spatial resolution), with a low measurement threshold (0.27 N/cm²) and is capable of high measurement frequencies (up to 500 Hz)(~temporal resolution) and as such allowed for a reliable COP determination even at low GRFs.

Nevertheless, the reliability of the COP determination (on which SI and IFCP determination is based) using the plantar pressure plate was not assessed and compared with a COP determination with a force plate. As such, you might argue that this first research question was not fully answered. We refer to appendix 3 and appendix 5 at the end of this thesis that present some theoretical considerations to show that COP calculations from plantar pressure measurements are less prone to measurement errors when small GRFs are exerted, which is the case at initial foot contact, than COP calculations from force plate data.

Moreover, the use of the plantar pressure plate allowed for a qualitative assessment of the COP-trajectory during the initial foot contact phase which resulted in the identification of a group of Atypical IRFC. Based on a qualitative assessment of the COP patterns 22% of runners showed this pattern at two or more speed conditions and 18% of all runners showed this pattern with both feet in 2 or more speed conditions. This indicates that this pattern should indeed be considered as a distinct IFCP.

The Atypical IRFC were characterized by an initial fast anterior displacement of the COP along the lateral shoe margin. At 3.2 $m \cdot s^{-1}$ these atypical IRFC are characterized by an earlier first metatarsal contact (4.0 ±2.0% of contact time)(~0.010s) compared to the typical IRFC (11.8 ±2.9% of contact time)(~0.030s). This timing can be used as a criterion to distinguish between the Atypical IRFC and the Typical IRFC. However, for the foot contacts with a first metatarsal contact between 6 and 8% of contact time a qualitative assessment of the COP trajectory is needed.

As study two has shown, the Atypical IRFC showed initial ankle and foot positioning in between the Typical IRFC and the IMFC, but more closely matching the IMFC. This explains why the determination of the foot-to-ground angle at initial foot contact as a kinematic method to determine IFCP (3) classified four out of eleven Atypical IRFC as IRFC and seven as IMFC and as such is not able to discern the Atypical IRFC form the other IFCPs. Moreover, if SI (to determine IFCP) is measured with a force platform, COP position at the very initial foot contact is not reliable (appendix 3) (44), and therefore a certain ground reaction force (GRF) threshold value is used (48). Given the fast initial anterior COP movement in the Atypical IRFC such method could possibly classify Atypical IRFC as IMFC.

To be able to detect the Atypical IRFC patterns high frequent plantar pressure measurements are needed. As the categorization of a foot contact into Typical or Atypical IRFC is based on the fast anterior displacement of the COP along the lateral shoe margin you need sufficiently high frequencies to be able to measure this. A quantitative measure for this phenomenon was derived from the time between initial contact and the first metatarsal contact (study 1). When running at 3.2 m/s the time until first metatarsal contact was about 0.030 s for the Typical IRFC (11.8 ± 2.9% of contact time) and about 0.010 s for the Atypical IRFC (4.0 ± 2.0% of contact time). Respectively, when measuring at 500 Hz this was 15 or 5 measurement frames. To be able to detect such short initial phases, measuring frequencies of 200 Hz or higher are advised. When measuring at frequencies below 200 Hz, the temporal resolution might be insufficient to detect the fast initial COP movement along the lateral shoe border.

1.2. What is the within-subject effect of running speed on IFCP?

Our first study confirmed that indeed **most runners show an IRFC but with increasing velocity some of these runners make a shift towards an IMFC or IFFC.** The IFCP group distributions as determined with an optimized SI method of 82% IRFC and 18% IMFC at 3.2 $m \cdot s^{-1}$ and 46% IRFC, 32% IMFC and 22% IFFC at 6.2 $m \cdot s^{-1}$ were mainly in accordance with previous research (11, 28). The higher percentage of IMFC and IFFC at the faster running speeds are caused by intra-individual changes towards more anterior IFCPs in 45% of the runners (~transition runners). A study by Forrester and Townend (21) analyzed the influence of running speed (2.2 - 6.1 $m \cdot s^{-1}$) on foot-to-ground angle, as a kinematic measure of IFCP. The authors found three clusters of runners: a group with anteriorly inclined foot-to-ground angles at all running speeds (30% of runners) (~IMFC or IFFC), a group with posteriorly inclined foot-to-ground angles at all running speeds (34% of runners) (~IRFC) and a group with posteriorly inclined foot-to-ground angles at speeds up to 4 $m \cdot s^{-1}$ and anteriorly inclined foot-to-ground angles at faster running speeds (36% of runners) (~transition runners). These findings confirm the intra-individual shift towards more anterior IFCPs with increasing running speed in some subjects.

Some research has suggested that there might be a performance benefit with IMFC or IFFC based on the larger percentage of IMFC and IFFC in elite runners compared to recreational runners (25, 27, 29). Our results however, suggest that the greater percentages of IMFC and IFFC in elite runners might just be a consequence of their faster running speeds rather than these IFCPs being beneficial for performance. This statement is supported by Larson *et al.* (30) who found no significant differences in marathon finishing times between the different foot strike pattern groups.

1.3. What are the kinematic differences between the inter-individually different IFCPs?

We hypothesized that the main kinematic differences between the different IFCPs are situated at the distal ankle and foot kinematics. Indeed, **significant differences in ankle and foot kinematics, especially at initial foot contact, were found between the different IFCPs** that are in line with previous research (3, 39, 46). In IRFC the foot touches the ground in a posteriorly tilted position after which the ankle shows an initial plantar flexion. In IMFC the foot lands in a flat or anteriorly tilted position after which the ankle immediately dorsiflexes. The Atypical IRFC showed initial ankle and foot configurations that were in between the Typical IRFC and the IMFC, but most closely matching the IMFC. That is, a slightly plantar flexed and a slightly posteriorly tilted foot.

We also observed more 'global running style' differences as the Typical IRFC had longer contact times, shorter flight times, a less vertical leg angle at initial contact and a lower k_{leg} than both Atypical IRFC and IMFC. Based on the similar global running style and few distal kinematic differences between the Atypical IRFC and the IMFC the Atypical IRFC might be hard to discern from an IMFC, without the use of specified measurements, and as shown in our first study might induce higher VILR.

In the following section we provide an overview of the main global running style and distal kinematics that were found to differ between the different IFCPs in the studies presented in this thesis. These differences show that the IFCP classification (based on optimized SI and time until first metatarsal foot contact) indeed results in a classification of runners with distinct different running styles. (Fig 1-2, table 1-3).

INITIAL FOOT CONTACT

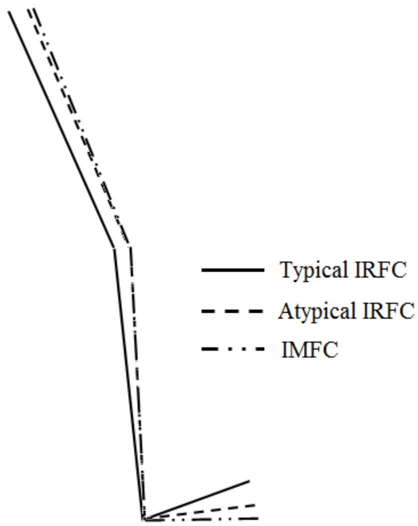

Figure 1: *Sagittal plane stick figure at initial foot contact representing the different IFCPs.*

COP-TRAJECTORY

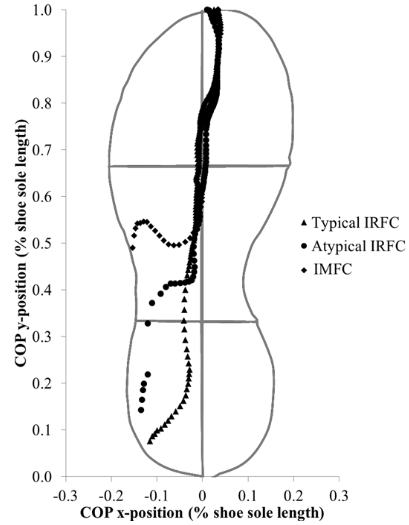

Figure 2: *Representative COP-trajectories of the different IFCPs.*

Table 1*: Global running style differences between the different IFCPs. Grey scales indicate significant differences.*

'Global running style' differences	**Typical IRFC**	**Atypical IRFC**	**IMFC**
Contact time (s)	0.254 ± 0.016	0.240 ± 0.016	0.238 ± 0.016
Flight time (s)	0.112 ± 0.019	0.126 ± 0.022	0.134 ± 0.025
k_{leg} ($kN \cdot m^{-1}$)	11.1 ± 1.9	13.6 ± 1.7	13.7 ± 1.6
k_{kne} ($N \cdot m \cdot ^{\circ -1} \cdot kg^{-1}$)	0.096 ± 0.017	0.132 ± 0.022	0.116 ± 0.016
k_{ankle} ($N \cdot m \cdot ^{\circ -1} \cdot kg^{-1}$)	0.155 ± 0.031	0.128 ± 0.029	0.121 ± 0.032
Knee flexion range of motion (°)	29.9 ± 4.1	25.5 ± 3.4	26.7 ± 4.0
Ankle dorsiflexion range of motion (°)	17.3 ± 2.8	21.3 ± 4.8	25.4 ± 4.5
Leg posterior inclination at initial contact (°)	22.0 ± 2.3	19.4 ± 1.4	18.3 ± 0.9

Table 2: *Distal kinematic differences between the different IFCPs. Grey scales indicate significant differences.*

'Distal' kinematic differences	**Typical IRFC**	**Atypical IRFC**	**IMFC**
Shank posterior inclination at initial contact (°)	6.0 ± 3.1	2.7 ± 2.2	3.3 ± 2.8
Ankle sagittal plane angle at initial contact (°)	7.2 ± 3.5	-3.1 ± 4.4	-10.4 ± 6.3
Initial ankle plantar flexion range of motion (°)	6.7 ± 1.9	0.9 ± 0.9	0.1 ± 0.3
Rearfoot sagittal plane inclination at initial contact	20.4 ± 4.8	7.0 ± 5.1	1.6 ± 3.1
Rearfoot frontal plane inversion at initial contact (°)	-9.5 ± 3.1	-15.0 ± 4.0	-17.5 ± 6.5
Rearfoot frontal plane eversion range of motion (°)	12.0 ± 3.0	16.4 ± 3.2	19.0 ± 4.7
Ankle frontal plane inversion at initial contact (°)	-6.4 ± 3.6	-9.2 ± 3.8	-10.9 ± 5.2
Ankle eversion range of motion (°)	15.8 ± 3.5	18.9 ± 3.7	20.6 ± 4.6
v_{TDheel} ($m \cdot s^{-1}$)	-1.18 ± 0.11	-1.08 ± 0.12	-0.97 ± 0.14

Table 3: *List of parameters that were found not to differ between the different IFCPs.*

NO significant differences in	
Step frequency	*Knee flexion at initial contact*
Step length	*Knee maximal flexion*
k_{vert}	*Ankle maximum dorsiflexion*
Thigh sagittal plane inclination at initial contact	*Ankle frontal plane maximum eversion*

These differences confirm the findings of previous studies comparing the kinematics between the different IFCPs (1, 3, 11, 31, 39, 46), indicating that the main kinematic differences between the different IFCPs are situated at the foot and ankle during the initial foot contact phase. Runners with an IRFC make initial contact with the ground with a slightly dorsiflexed ankle and posteriorly inclined foot position and a more posteriorly inclined leg angle. Whereas the Atypical IRFC and IMFC make initial contact with the ground with a slightly plantar flexed and a 'flat' or slightly anteriorly inclined foot position. Also, through a greater knee flexion range of motion the Typical IRFC have a slightly longer contact time than the other IFCP, but no differences in step frequency were found between the different IFCPs.

The past decade, some novel running styles such as Pose (5, 18) and Chi running (http://www.chirunning.com/) have been developed, claiming to reduce injury susceptibility and increase running economy. However, these claims still need to be validated. Both Pose and Chi running styles are characterized by an IMFC or IFFC, a 'tall' body alignment, a high step frequency and a forward lean (fig. 3). In a study by Arendse *et al.* (5) a group of recreational runners trained the Pose running style. After the training, subjects indeed showed an IMFC, an increased step frequency of around 3.49 Hz and shorter step lengths of about 0.83 m at 2.9 $m \cdot s^{-1}$. Compared to these 'Pose runners', the IMFC subjects in our studies showed a lower stride frequency of about 2.80 Hz and step length of about 1.09 m at 3.2 $m \cdot s^{-1}$ indicating that probably none of our subjects performed a natural Pose running style.

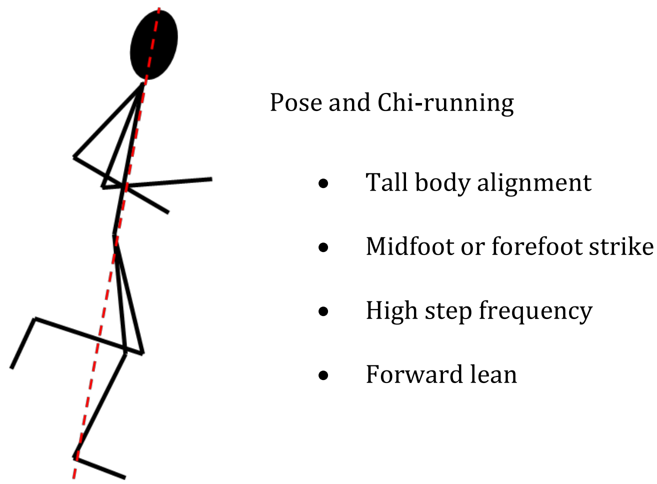

Figure 3*: Pose and Chi-running characteristics*

1.4. What is the difference in impact intensity, as measured with VILR, between the different IFCP types?

In our first study, impact intensity was assessed with VILR. We hypothesized that subjects with an IRFC show higher VILRs than subjects with IMFC or IFFC. However, in our first study we have shown that the **IRFC can be subdivided into Typical and Atypical IRFC** and after this subdivision **no difference in VILR was found between the IMFC and Typical IRFC while the Atypical IRFC showed the highest VILR for all studied running speeds (3.2 – 6.2 m·s^{-1}).** IFFC showed the lowest VILR at all running speeds. This implies that in previous studies where IRFC were not subdivided into Typical IRFC and Atypical IRFC the observed differences in impact intensity between IRFC and IMFC might need some reconsideration. Making initial contact with the ground with a posteriorly inclined foot and dorsiflexed ankle (~rearfoot ‘strike’) might not be the running style that evokes the highest impact.

1.5. What is the relationship between the observed kinematic differences between the different IFCPs and the impact severity, as measured with VILR?

In the second study we assessed the relationship between kinematics and VILR between the different IFCPs. We found that **for the IRFC subjects** (Typical and Atypical IRFC) the foot angle at initial foot contact, contact time and knee flexion range of motion were able to predict 53% of the inter-subject differences in VILR. As hypothesized, indeed **the distal kinematics of the foot (~initial foot position) showed the greatest correlation with VILR** (r=-0.68) indicating that a more posteriorly inclined foot position or more pronounced IRFC corresponded with a lower VILR. As the Atypical IRFC showed an initial foot contact with an only slightly posteriorly inclined foot position, they limit the possibility of an initial ankle plantar flexion, which has been shown to be an effective impact reducing mechanism (22) and the use of the cushioning properties of the heel part of the shoe and the heel fat pad (17, 49). The common belief that pronounced 'heel striking' induces the greatest VILR should be reconsidered.

We also found that **global running style parameters such as contact time, knee flexion range of motion, k_{leg}, k_{knee}, leg angle at initial contact were significantly correlated with VILR.** This indicates that also the dynamics of more proximal segments, such as thigh and trunk and/or the total body center of mass mechanics might influence the impact of running as measured with VILR. These findings confirm the statement of previous research by Bobbert *et al.* (7) and more recently Clark *et al.* (16) that stated that the initial GRF is generated by a superimposition of both distal segment decelerations and the deceleration of the rest of the body.

1.6. Does the spatial distribution of the VGRF impact intensity over different foot zones differ in runners with different IFCPs?

In the third study we assessed the spatial distribution of the impact intensity over different foot zones (rearfoot, midfoot and forefoot) in runners with different IFCPs. Impact intensity was measured both with VILR and with the magnitude of the peak high frequency component of the

VGRF, per foot zone. As hypothesized, we found that in the Typical IRFC the greatest impact intensity was situated under the rear- and midfoot zone, while for the IMFC the greatest impact intensity was situated under the mid- and forefoot zone. For the Atypical IRFC the greatest impact intensity was situated under the midfoot zone. These findings indicate that **IFCP indeed is related to the spatial distribution of the VGRF impact intensity under the foot**. Also these findings indicate that for passive impact intensity reduction the **different IFCPs would benefit from cushioning in different zones of the shoe**.

2. BEYOND THE RESEARCH QUESTIONS

2.1. Have we gained new insights in the mechanics of the impact intensity of running?

Kinematic impact reducing strategies

In the first study we confirmed that different IFCPs are characterized by differences in impact intensity, as measured with VILR. In the second study we have shown that both distal ankle and foot kinematics (especially at initial foot contact) and global running style characteristics are related to the impact intensity differences between different IFCPs. Different IFCPs use different kinematic strategies to cope with the impact of running. Typical IRFC perform an initial ankle plantar flexion (with eccentric tibialis anterior work) during which also the cushioning heel partition of the shoe and the heel fat pad reduce the impact of running. The pronounced posteriorly tilted foot position at initial foot contact allows the Typical IRFC to use these strategies. The limited posterior inclination of the foot at initial foot contact in the Atypical IRFC limit the possible use of these strategies which could explain the observed higher VILR in these subjects. IMFC perform an initial ankle dorsiflexion to reduce the impact. The plantar flexed ankle at initial foot contact allows the IMFC to use this strategy. Additionally, the Typical IRFC show longer contact times and greater knee flexion range of motions which allow a slower deceleration of the more proximal masses (~upper body) and as such limit the contribution of the deceleration of the 'rest of the body' to the VILR.

VGRF derived measures for impact intensity

In the third study we have assessed the impact intensity differences between the different IFCPs by determining the peak of the high frequency VGRF component (>10Hz). The decomposition of the VGRF into low and high frequency components allows to separate the impact characteristics of the VGRF from the rest of the GRF. Atypical and Typical IRFC showed greater high frequency peak VGRF than the IMFC. The decomposition of the VGRF into low frequency (~non-impact) and high frequency (~impact) component is analogues to the decomposition of the VGRF into the contributions to the VGRF of the decelerations of the distal segments (~stance leg) and rest of the body (~swing leg and upper body) deceleration (7, 8, 16, 19, 43). It is assumed that the fast deceleration of the stance leg during the initial impact phase generates the peak high frequency VGRF during the initial impact phase. The magnitude of the peak of the high frequency VGRF component can be regarded as a measure for impact intensity. Shorten *et al.* (42, 43) have shown that the magnitude of the impact peak of the non-decomposed VGRF signal is not suited as an impact intensity measure as it is composed of both low frequent and high frequent components.

VILR, another more frequently used impact intensity measure, is calculated on the non-decomposed VGRF signal and therefore includes both the low and high frequency components of the VGRF signal. As such, VILR also contains a low frequent signal part, but regardless of the "origin" it describes the loading of the entire force acting under the foot on the plantar foot structures and on the shoe sole. As we found a greater impact intensity in the Atypical IRFC when compared with the Typical IRFC when measured with VILR, but not when measured with the peak high frequency VGRF component, we hypothesize that in the Atypical IRFC a greater contribution of the deceleration of the 'rest of the body' contributes to the VILR than in the Typical IRFC. This hypothesis is supported by the observed shorter contact times in the Atypical IRFC which indicate a faster deceleration of the total body mass. However, regardless of which impact intensity measure was used, the Atypical IRFC showed the highest impact intensity, and the IMFC the lowest impact intensity.

Segmental contributions to the VGRF during the initial impact phase

In the introduction we posed the research purpose to calculate the segmental contributions to the VGRF for runners with different IFCPs in order to gain insights in the aetiology of the impact intensity differences. This analysis was not retained in one of the published/submitted studies. However, we did conduct such analysis for the running trials at 3.2 $m{\cdot}s^{-1}$ (same subjects and IFCP groups as in the second study). In these analysis the contribution of each segment to the VGRF during the initial impact phase was determined by calculating the deceleration in the vertical direction of each segment based on the 3D kinematic data. A main limitation was that we only recorded stance leg kinematics. As a consequence, the contribution of the swing leg and the upper body were not calculated. The VGRF is composed of a superimposition of both distal segment decelerations and the deceleration of the 'rest of the body'. Therefore, based on our analysis we can only assess the contributions of the stance leg decelerations. As we know from study 1 and study 2 the Atypical IRFC and IMFC have shorter contact times and longer flight times than the Typical IRFC, which indicates a faster deceleration of the total body mass, it seems reasonable to hypothesize a greater contribution of the 'rest of the body' to the VILR in the Atypical IRFC and IMFC.

Figure 4 shows the VGRF contributions of the stance leg segments (forefoot, rearfoot, shank and thigh) for the different IFCPs. For each segment we calculated the vertical touchdown velocity 1 frame (0.005s) before initial contact, the vertical peak force, time of peak force, the impact impulse (force-time integral during the initial impact phase (first 0.050s of foot contact)) and the average loading rate from minimum to maximum force during the initial impact phase (table 4-7). These variables were selected as they could be related to, or measure the contribution of each segment to, the VGRF during the initial impact phase and as such the impact intensity. In each of the following tables the significant between-IFCP differences are highlighted using grey-scales.

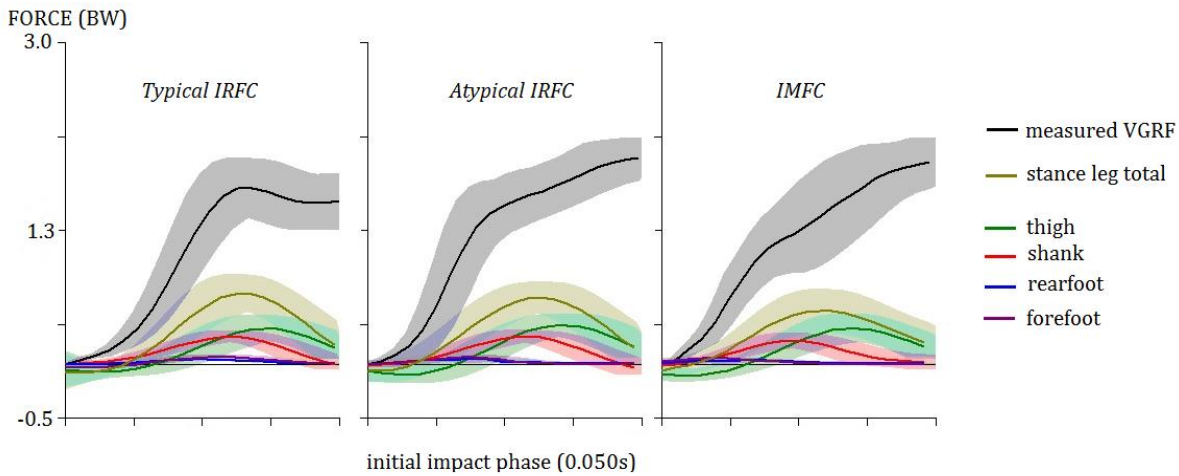

***Figure 4**: Contribution of the stance leg segmental accelerations to the VGRF for the different IFCPs (3.2 m·s^{-1})*

No differences in peak force of the rearfoot, shank, thigh or total stance leg were found between the different IFCPs. For the forefoot segment we found the lowest peak force in the IMFC. Also the peak force from the rearfoot, forefoot and shank segments was reached later in the Typical IRFC. (table 4)

***Table 4**: Segment peak force and time of peak force per IFCP.*

	Typical IRFC	Atypical IRFC	IMFC
Leg Fmax (BW)	0.699 ± 0.150	0.643 ± 0.153	0.559 ± 0.218
Time leg Fmax (s)	0.033 ± 0.004	0.031 ± 0.004	0.031 ± 0.004
Thigh Fmax (BW)	0.366 ± 0.109	0.411 ± 0.082	0.378 ± 0.135
Time thigh Fmax (s)	0.040 ± 0.009	0.039 ± 0.010	0.036 ± 0.006
Shank Fmax (BW)	0.276 ± 0.053	0.281 ± 0.057	0.242 ± 0.081
Time shank Fmax (s)	0.031 ± 0.003	0.028 ± 0.004	0.025 ± 0.003
Rearfoot Fmax (BW)	0.049 ± 0.008	0.055 ± 0.013	0.048 ± 0.012
Time rearfoot Fmax (s)	0.025 ± 0.003	0.019 ± 0.004	0.016 ± 0.004
Forefoot Fmax (BW)	0.080 ± 0.015	0.081 ± 0.010	0.064 ± 0.014
Time forefoot Fmax (s)	0.028 ±0.004	0.018 ± 0.006	0.010 ± 0.003

No differences in touchdown velocity of the rearfoot, shank, thigh or total stance leg were found between the different IFCPs. For the forefoot segment we found the smallest touchdown velocity in the IMFC.

Table 5: *Stance leg segment touchdown velocity per IFCP.*

	Typical IRFC	**Atypical IRFC**	**IMFC**
Leg vertical touchdown velocity ($m \cdot s^{-1}$)	-0.70 ±0.13	-0.74 ±0.14	-0.74 ± 0.13
Thigh vertical touchdown velocity ($m \cdot s^{-1}$)	-0.55 ± 0.16	-0.61 ± 0.17	-0.63 ± 0.13
Shank vertical touchdown velocity ($m \cdot s^{-1}$)	-0.83 ± 0.11	-0.85 ± 0.13	-0.84 ± 0.16
Rearfoot vertical touchdown velocity ($m \cdot s^{-1}$)	-1.14 ± 0.12	-1.12 ± 0.15	-1.04 ± 0.16
Forefoot vertical touchdown velocity ($m \cdot s^{-1}$)	-1.44 ± 0.17	-1.54 ± 0.21	-1.30 ± 0.20

We found a higher average rearfoot loading rate in the Atypical IRFC compared with the Typical IRFC and a lower forefoot average loading rate in the IMFC when compared with the Typical and Atypical IRFC.

Table 6: *Stance leg segment average loading rate per IFCP.*

	Typical IRFC	**Atypical IRFC**	**IMFC**
Leg average loading rate ($BW \cdot s^{-1}$)	26.90 ± 6.37	26.31 ± 8.45	21.23 ±10.4
Thigh average loading rate ($BW \cdot s^{-1}$)	14.61 ± 5.35	17.08 ± 6.29	16.71 ± 7.13
Shank average loading rate ($BW \cdot s^{-1}$)	9.09 ± 2.18	10.92 ± 3.53	10.15 ± 3.91
Rearfoot average loading rate ($BW \cdot s^{-1}$)	2.16 ± 0.50	2.87 ± 1.21	2.40 ± 0.65
Forefoot average loading rate ($BW \cdot s^{-1}$)	4.66 ± 1.41	5.02 ± 0.87	3.21 ± 0.79

The Typical IRFC showed the highest force impulse from the shank segment compared to the other IFCPs. (table 7)

Table 7: *Stance leg segment force impact impulse per IFCP.*

	Typical IRFC	**Atypical IRFC**	**IMFC**
Leg force impact impulse (BW·s)	0.015 ± 0.003	0.014 ± 0.003	0.013 ± 0.004
Thigh force impact impulse (BW·s)	0.0065 ± 0.0024	0.0066 ±0.0023	0.0060 ± 0.0022
Shank force impact impulse (BW·s)	0.0059 ± 0.0007	0.0053 ± 0.0006	0.0047 ± 0.0013
Rearfoot force impact impulse (BW·s)	0.0011 ± 0.0001	0.0011 ± 0.0001	0.0011 ± 0.0001
Forefoot force impact impulse (BW·s)	0.0012 ± 0.0001	0.0013 ± 0.0002	0.0012 ± 0.0002

Although we observed differences in impact intensity (VILR and peak high frequency VGRF component) between the different IFCPs, the analysis of the segmental contribution to the VGRF was only partially able to explain these differences as we only found small or subtle differences between the different IFCPs. Some findings support the higher VILR in the Atypical IRFC compared to the Typical IRFC. That is, the Atypical IRFC showed shorter contact time (~faster 'rest of body' deceleration), an earlier peak force of the rearfoot, forefoot and shank segment (~faster deceleration of these masses) and a higher average loading rate of the rearfoot segment force (~faster, more impact like deceleration). However, some results couldn't confirm the VILR differences or even contradict them. That is, when compared with the Typical IRFC the Atypical IRFC showed no difference in peak segment force magnitudes and touchdown velocities, no difference in forefoot, shank and thigh average segment force loading rate and even a lower shank segment force impact impulse. This might be explained by the possible greater contribution of the deceleration of the 'rest of the body' in the Atypical IRFC, given their shorter contact times.

Some findings support the higher impact intensity in the Atypical IRFC compared to the IMFC. That is, the Atypical IRFC showed a higher peak forefoot segment force, a higher forefoot touchdown velocity and a higher forefoot segment force average loading rate (~more impact like fast deceleration). However, we found no difference in force peak magnitude, touchdown velocity, average loading rate or force impact impulse of the rearfoot, shank and thigh segments between the Atypical IRFC and IMFC.

Several possible explanations for the lack of differences in segmental decelerations supporting the impact intensity differences between the different IFCPs can be found:

- With our analysis we did not calculate the contributions to the VGRF of the swing leg and the upper body which might be more important than one would expect in explaining the impact intensity of the VGRF during the initial impact phase.

- Methodological issues with detecting fast, high frequent motions using 3D motion capture systems (e.g. Qualisys):
  - Our motion capturing system operated at 200 Hz. To focus on impact intensity higher measuring frequencies are favorable.

- To detect 3D kinematics, lightweight retro-reflective markers were attached to the skin and on thermoplastic plates. Skin and plate movements and inertia might limit the detection of very fast (high frequency) motions of the different segments (and bones).
- To calculate the segment contributions to the VGRF, segment accelerations are calculated as the second derivative of the positional data of each segment. In order to obtain reliable and interpretable second derivative data, the original positional data needs to be sufficiently low pass filtered. Cut-off frequencies of at least 40Hz and for some segments even 20 Hz were used. This procedure might cut-out some high frequent (~impact like) motions.
- Besides the low pass filtering of marker data also the construction of a kinematic multi-segment model (Visual 3D) could remove some high frequent motions. Each segment is determined by a set of anatomical markers (on the skin, preferably at bony points) defining the segment dimensions and a set of tracking markers (on skin or thermoplastic plates) to define the segment motions. In constructing a kinematic multi-segment model each segment is defined as the best possible fit through the different tracking markers. Such procedure might also cause some cutting out of high frequent motions.

In other words, even with the use of an advanced motion capture system, determining the segmental contributions to the VGRF in order to gain more insights in impact intensity differences in running remains challenging. Based on our findings we can provide some considerations for future research:

- The newest motion capture systems (e.g. Qualisys Oqus 3+ or Vicon T10S) are able to capture at frame rates of 500 Hz (even higher with reduced field of view or resolution) and should allow a more detailed calibration and as such could be better suited for fast and small movements (e.g. the impact phase in a running foot contact).
- Both anatomical as tracking markers should be attached as firmly as possible, preferably at bony point to be able to detect the skeletal motions as closely as possible. E.g. it might be better to attach the shank tracking markers straight to the skin at the location of the

distal frontal tibia surface, instead of using thermoplastic plates, with markers attached on it, taped around the shank.

- The contribution of the swing leg and the upper body to the impact intensity might be substantial and should be incorporated in future research.

2.2. IFCP and joint moment, power and work

IFCP has not only been shown to be related to the impact intensity during the initial impact phase, but could also influence the loading at the knee and ankle joint during the weight acceptance and propulsion phase of foot contact. Williams *et al.* (46) have shown that when runners shift from a IRFC to an IFFC this results in decreased eccentric extension work at the knee and increased eccentric plantar flexion work at the ankle and as such is more demanding for the plantar flexor muscles, Achilles tendon and plantar fascia. These findings were confirmed in a more recent study (47) where indeed a greater work demand and greater peak eccentric power at the knee extensors was found when running with an IRFC compared to an IFFC. Almonroeder *et al.* (2) have shown, with muscle modeling and dynamic simulations of running, that when runners adopt a non-IRFC compared to an IRFC indeed they experience higher Achilles tendon impulses.

Together with the often decreased impact loading in IFFC when compared with IRFC, some researchers have suggested that shifting from an IRFC to an IFFC might be beneficial for subjects suffering from patellofemoral pain syndrome due to a possible decrease in the loading at the knee joint (13, 40). In our second study we have shown that Atypical IRFC might have a higher stress fracture injury susceptibility due to a higher VILR when compared with the other IFCPs. However, loading at the different joints was not incorporated in our published/submitted studies, and could also be very useful information with regard to injury prevention/treatment. Therefore, we additionally assessed the loading of the muscles crossing the knee and ankle joint for the different IFCPs. We determined peak joint moment, peak eccentric power and eccentric work. Eccentric muscle activity is more strenuous than concentric contraction. Therefore the peak eccentric power and eccentric work were used as variables to assess the loading of the muscles crossing the knee and ankle joint.

The data for these analyses were the same as in the second study in this thesis: 52 runners, left foot contacts at 3.2 $m \cdot s^{-1}$. The kinematic model that was used to determine ankle and knee kinematics is described in appendix 2. Ankle and knee joint moment and power were calculated with a standard inverse dynamics approach using cardan sequence. GRF were filtered with a Butterworth low pass filter with a cutoff frequency of 80 Hz, kinematics with a cutoff frequency of 20 Hz. Individual joint moment and power curves were checked for possible measurement artefacts due to the used methods (appendix 4). Peak moments, peak eccentric and concentric power and eccentric and concentric work were compared between the different IFCPs using ANOVA and post-hoc analyses with Bonferroni correction. All analyses were performed in SPSS 22 and significance level was set at $p<0.05$.

Ankle parameters are presented in table 8, knee parameters in table 9. Time curves are shown in figure 5.

Table 8: *Ankle joint moment, power and work parameters for the different IFCPs.*

	Typical IRFC	Atypical IRFC	IMFC
Ankle joint			
Peak internal plantar flexion moment (Nm)	$171.0 \pm 28.9^{b,c}$	189.8 ± 18.6^{a}	209.1 ± 21.1^{a}
Peak eccentric plantar flexion power (W)	$442.0 \pm 76.7^{b,c}$	$544.4 \pm 161.9^{a,c}$	$651.2 \pm 89.3^{a,b}$
Eccentric dorsiflexion work (J)	$1.11 \pm 0.81^{b,c}$	0.07 ± 0.07^{a}	0.00 ± 0.00^{a}
Eccentric plantar flexion work (J)	$23.98 \pm 4.94^{b,c}$	$32.57 \pm 9.69^{a,c}$	$41.60 \pm 6.97^{a,b}$
Total eccentric work (J)	$25.08 \pm 5.09^{b,c}$	$32.64 \pm 9.66^{a,c}$	$41.60 \pm 6.97^{a,b}$
Peak concentric plantar flexion power (W)	678.2 ± 129.4	717.4 ± 157.1	744.0 ± 116.5
Concentric plantar flexion work (J)	42.36 ± 8.94	46.38 ± 7.41	48.49 ± 6.74

[a] significant difference from Typical IRFC, $p<0.05$
[b] significant difference from Atypical IRFC, $p<0.05$
[c] significant difference from IMFC, $p<0.05$

Table 9:*Knee joint moment, power and work parameters for the different IFCPs.*

	Typical IRFC	Atypical IRFC	IMFC
Knee joint			
Peak internal extension moment (Nm)	190.9 ± 41.3^{b}	$221.9 \pm 31.5^{a,c}$	175.6 ± 27.6^{b}
Peak eccentric extension power (W)	1216.9 ± 278.2^{c}	1220.7 ± 236.1^{c}	$786.4 \pm 199.8^{a,b}$
Eccentric extension work (J)	48.77 ± 11.71^{c}	49.37 ± 9.32^{c}	$34.39 \pm 7.97^{a,b}$
Peak concentric extension power (W)	406.7 ± 118.9	421.8 ± 124.7	315.2 ± 74.6
Concentric extension work (J)	23.22 ± 5.36	25.25 ± 6.88	19.50 ± 4.38

[a] significant difference from Typical IRFC, $p<0.05$
[b] significant difference from Atypical IRFC, $p<0.05$
[c] significant difference from IMFC, $p<0.05$

As already shown in previous research (46, 47) we indeed found a higher peak eccentric power and eccentric work at the ankle joint in the IMFC compared with the Typical IRFC. The Typical IRFC showed the lowest peak moment, peak eccentric power and eccentric work at the ankle joint (table 8). At the knee joint the IMFC showed the lowest peak eccentric power and eccentric work compared with the Typical and Atypical IRFC. The Atypical IRFC showed the highest peak knee joint moment (table 9). These results are in line with previous research. However, we used an inter-subject approach comparing groups performing their habitual IFCP. Whereas in previous studies an intra-individual design was used in which subjects performed both IRFC and IFFC running styles (13, 46, 47). However, Williams *et al.* (46) have shown that runners are able to alter their IFCP from an IRFC to an IFFC that is mechanically similar to that of a practiced IFFC.

Our results indicate that running with an IRFC might indeed place higher demands at the knee joint compared with an IMFC and as such switching to an IMFC might be beneficial for subjects suffering from knee pathologies. However IMFC has shown to place higher demands on the ankle joint and as such could possibly be ill-advised for subjects suffering from plantar fasciitis or Achilles tendinopathy. Moreover, as already stated in the second study, caution should be exercised when shifting from an IRFC to an IMFC. Subjects might end up with an Atypical IRFC as this IFCP only shows small differences in distal initial ankle and foot kinematics with IMFC, but might provoke an increased VILR. These additional analyses also showed that the Atypical IRFC show no difference in peak knee eccentric power and work compared to Typical IRFC.

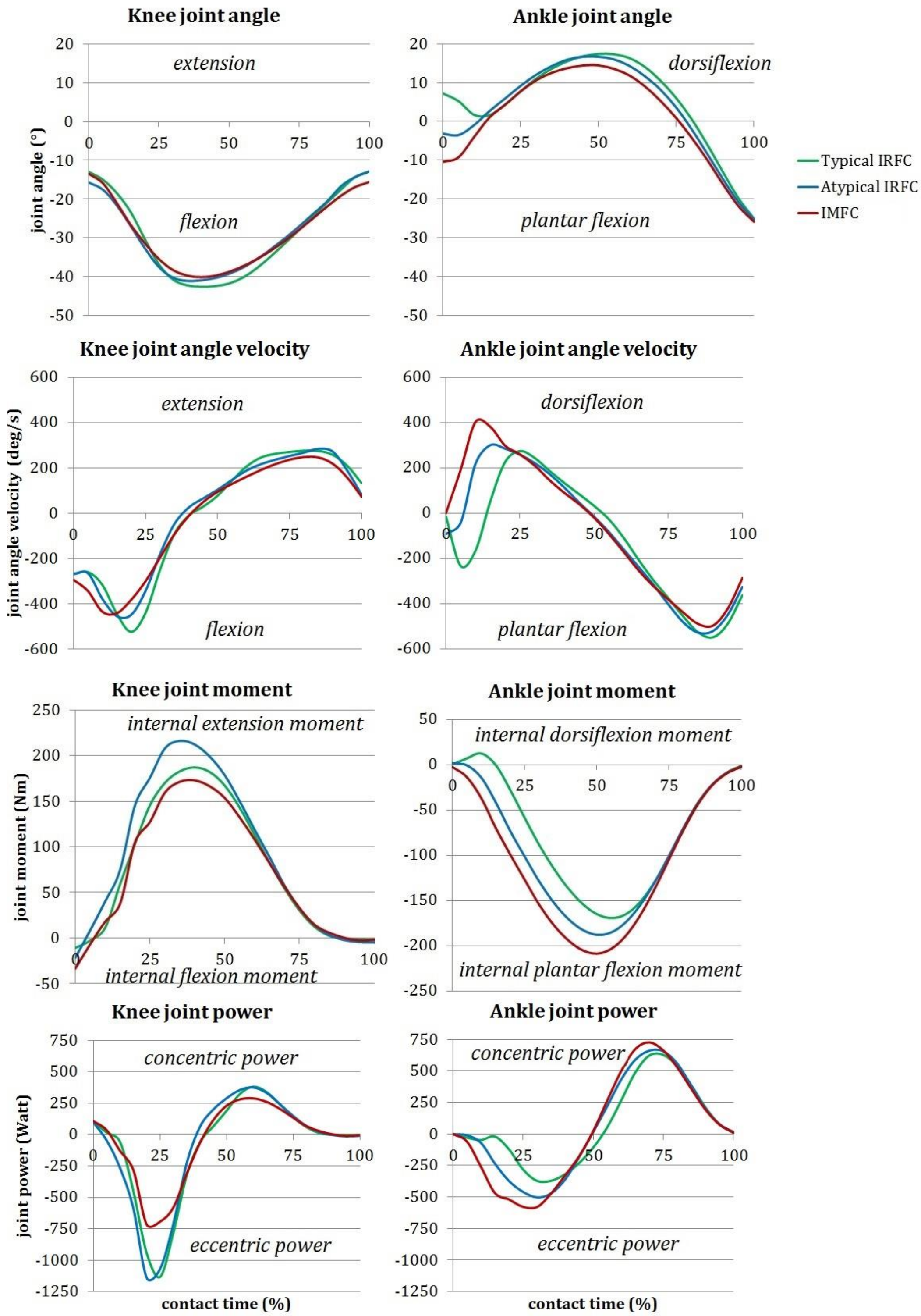

Figure 5: *Knee and ankle joint angle, angular velocity, moment and power for the different IFCPs at 3.2* $m{\cdot}s^{-1}$.

These findings indicate that deliberately changing IFCP from Typical IRFC to IMFC in order to decrease impact intensity or loading at the knee should be done with caution. In our first study we found no difference in impact intensity between Typical IRFC and IMFC. In our second study we have shown that there are only small kinematic differences between Atypical IRFC and IMFC and that the distal ankle and foot kinematics of the Atypical IRFC lie in between Typical IRFC and IMFC. This means that when shifting from an IRFC to an IMFC one might end up with an Atypical IRFC which could increase VILR and would possibly not result in a decreased loading at the knee. Moreover, IMFC and Atypical IRFC have shown to place higher demands at the ankle joint compared to the Typical IRFC. In other words, running with a Typical IRFC might reduce loading at the ankle while running with an IMFC could reduce loading at the knee, but increase loading at the ankle joint. Future prospective research should determine whether shifting IFCP from an IRFC to an IMFC or IFFC as a gait retraining method can reduce patella-femoral pain syndrome related pain or injury susceptibility and if this would not increase injury risk at the ankle joint (e.g. Achilles tendinopathy or plantar fasciitis).

Gerritsen *et al.* (22) have stated that the initial plantar flexion in IRFC functions as an impact reducing mechanism. The authors stated that the mechanism behind this could be found in the preactivation of the tibialis anterior muscle. As a greater foot-to-ground angle at initial contact increases the consecutive eccentric lengthening of the tibialis anterior muscle and more energy is absorbed by this muscle impact forces are lowered. In our study we indeed found that a more posteriorly inclined foot at initial foot contact is correlated with a lower VILR. And with these additional joint moment, power and work data we can further confirm these statements. We found a significant correlation between VILR and eccentric dorsiflexion work at the ankle (during the initial plantar flexion) ($p<0.001$, $r=0.594$)(for the Typical and Atypical IRFC) indicating that how more negative eccentric dorsiflexion work how smaller the VILR.

2.3. Impact testing of footwear

In our third study we have assessed the spatial force distribution under the foot during the initial impact phase with *in vivo* subject testing. We assessed the magnitude and loading rate of the different foot zones forces which could provide useful guidelines for *in vitro* mechanical testing of cushioning characteristics of athletic footwear. The current standard mechanical testing procedure is the ASTM F-1976 impact test (ASTM F1976-13, Standard Test Method for Impact Attenuation of Athletic Shoe Cushioning Systems and Materials, ASTM International, West Conshohocken, PA, 2013, www.astm.org). This is a gravity-driven test in which a 8.5 kg mass is dropped from a height of 30-70 mm on the heel and forefoot region of whole intact athletic shoe cushioning systems. An athletic shoe cushioning system is defined as all the layers of material between the wearer's foot and the ground surface that are normally considered a part of the shoe (~outsole, midsole, insole, …). During these tests force-time and force-deformation are measured. Shorten *et al.* (2011) performed this protocol on 224 running shoe heels with a 5.0 ± 0.05 Joules total energy input (~ dropping an 8.5kg mass from a 6 mm height)(fig. 6). They recorded peak force magnitudes ranging from 700-1400 N with a timing of 0.010-0.020 s. In our *in vivo* study, for all analyzed subjects, the measured forces under the heel during a running foot contact showed peak magnitudes ranging from 25-1225 N (average of 450 N) with a timing of 0.019-0.058s after initial contact. Based on the reported force-time curves by Shorten *et al.* (2011) we estimate an average loading rate of 66.7 kN·s^{-1} (~ peak of 1000N in 0.015s). In our *in vivo* subject testing average loading rates of the heel zone ranged from 0.5-40.8 kN·s^{-1} (average of 15 kN·s^{-1} or a peak of 450N in .030s).

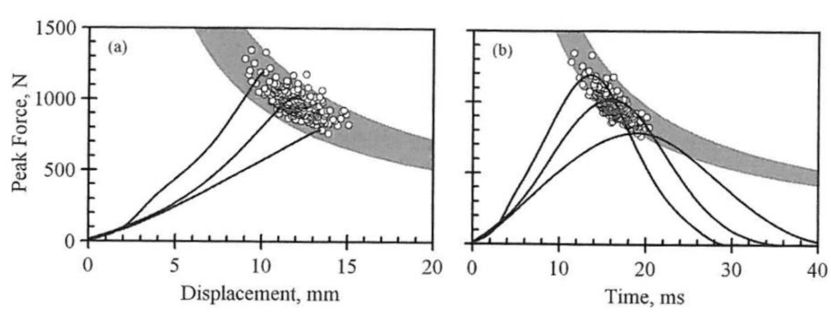

***Figure 6**: Adopted from Shorten et al.* (43)*: Results from the ASTM F1973-06 impact test of 224 running shoe heels showing relationships of peak impact force to (a) peak displacements and (b) time to peak.*

In the *in vitro* impact testing a mass of 8.5 kg is dropped from 6 mm height. This would result in a vertical touchdown velocity of -1.08 m·s^{-1}. In our second study we assessed the vertical touchdown velocity of the heel and found comparable values ranging from -0.75 to -1.21 m·s^{-1} with an average of -1.12 m·s^{-1} for all subjects. (Table 10)

Table 10*: Overview of heel zone impact loading variables.*

Heel zone impact loading	***In vitro*** **(Shorten 2011)** ASTM F-1976	***In vivo*** (study 2)
Peak force (N)	700-1400	25-1225 (mean 450)
Time peak force (s)	0.010-0.020	0.019 – 0.058 (mean 0.031)
Average loading rate (kN·s^{-1})	66.7	0.5-40.8 (mean of 15)
Touchdown velocity (m·s^{-1})	-1.08	-0.75 to -1.21 (mean -1.12)

When comparing the results from the in vitro and the in vivo testing we can conclude that *in vitro* testing with the ASTM F-1976 procedure results in a loading with greater peak force magnitudes and with faster average loading rates than were measured during the *in vivo testing* in our third study. The results from our third study could possibly be used to develop adjusted mechanical impact testing modalities. However, we must note that our results were obtained for subjects running in one type of running shoe (Li Ning Magne, Breine *et al.* 2014). Moreover, Shorten *et al.* (2010, 2011) have shown that the force under the heel consist of both high frequent impact-like as low frequent signal content, which could partially explain why sometimes the expectations based on *in vitro* measurements cannot be confirmed by *in vivo* subject testing. This also highlights the challenge to develop mechanical testing procedures that are a realistic representation of the in vivo loading.

In our third study we have shown that not only the heel zone, but also the midfoot zone is equally or even more loaded during the initial impact phase. In all IFCPs, but most explicitly in the Atypical IRFC, the midfoot zone also shows a force build up that is typical for impact like loading (rising part of the curve). This part of the shoe might be as important, or even more important for some runners (Atypical IRFC or IMFC), as the heel zone to provide passive cushioning and as such should also be tested using mechanical impact testing procedures.

2.4. Preparation of IFCP

We know that different IFCPs are characterized by differences in their sagittal plane foot position at initial foot contact. But how does one achieve a certain IFCP or in other words, how is IFCP prepared during (terminal) swing? As no difference in sagittal plane thigh angle was found between the different IFCPs, foot position (and as such IFCP) must be determined by knee (or shank, since no difference in initial thigh position was found) or ankle movements. We calculated the correlation between sagittal plane shank (as a representation of knee action) and ankle angle, during terminal swing (0.050 s before initial foot contact), with the sagittal plane foot position at initial foot contact. For these analysis we used the dataset from the second study. As kinematic data was captured at 200 Hz, we analyzed 10 measuring frames before initial foot contact. For each of these frames the correlation with foot position at initial contact was calculated and as such the evolution of each of these correlations was plotted from 0.050 s before until initial foot contact. (Figure 7)

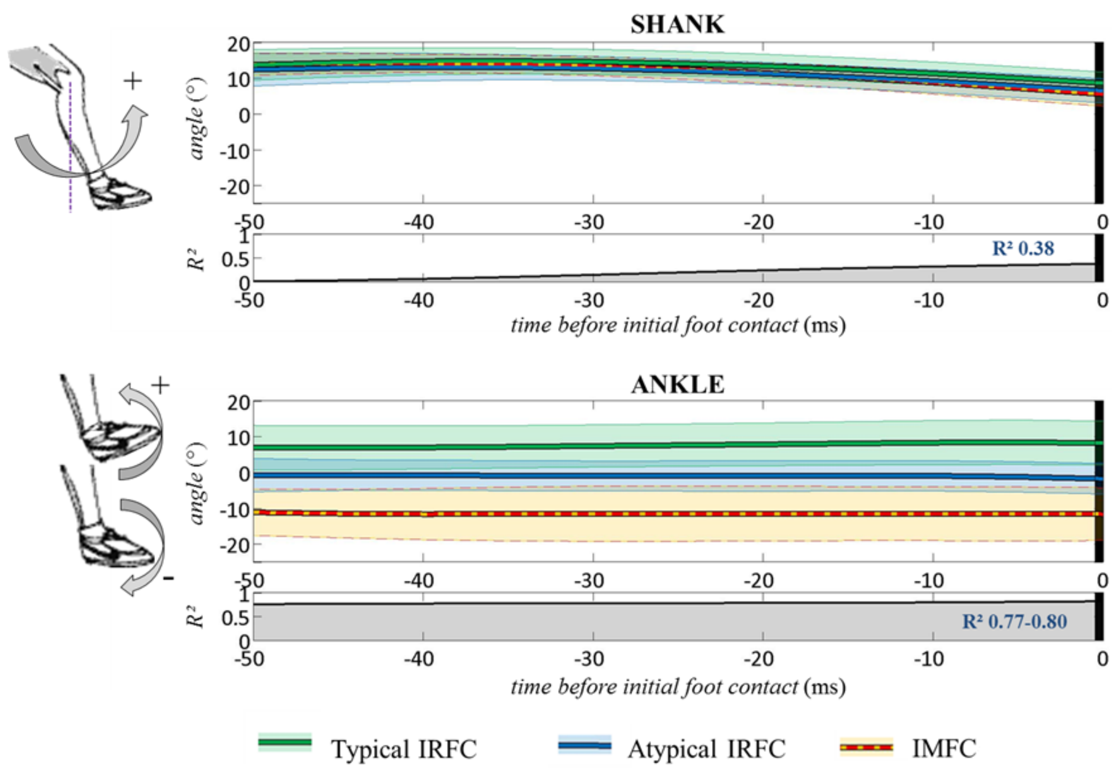

***Figure** 7: Evolution of the sagittal plane shank and ankle angle during terminal swing for the different IFCPs. Under the shank and ankle graph the evolution of the correlation (R²) with foot position at initial foot contact is given.*

We found that the contribution of the knee to the foot position at initial foot contact, as represented by the shank position, increased during the terminal swing and at initial foot contact was able to predict 38% of the variance in foot angle. The ankle angle however showed to be more important in determining the foot position as 77-80% of variance in foot angle could be attributed to the ankle angle. As shown on the graphs it is clear that the differences in ankle angle, determining the differences in initial foot position are already present before 0.050 s before initial foot contact. Further research should determine at which point in the swing phase these differences start arising. Taken together, these findings show that IFCP is mainly prepared by a distal regulation at the ankle with a significant, but smaller, contribution at the knee.

3. LIMITATIONS

As all data for this thesis was collected during one large testing campaign, most limitations are equally applicable to all studies presented in this thesis. A first limitation is that all subjects wore the same neutral shoe. This choice was made to counter the possible bias of shoe type and the neutral design was carefully selected as a good midway between all current running shoe types used by the average distance runner. However, this still means that some subjects had to run in a shoe type different from their habitual running shoe type. Although adaptation (to the shoes and the different running speeds) was included in the testing design this could have influenced their 'natural' IFCP. We know that shoe characteristics can influence IFCP and VGRF characteristics (6, 12, 36) which means that the obtained results are specific to the shoe used in the present study. No subjects reported to feel uncomfortable when running in these shoes. Also different types of running shoes were worn within all IFCP groups. As such, we do not believe that the experimental shoe biased our results. In future research, adding a condition in which subjects run in their own shoes could anticipate the aforementioned shoe-related bias or limitations.

Another limitation is that all our data was collected during indoor testing on a running track. This is not the 'natural' environment of distance runners which could have influenced our results, although a short habituation to the running track and shoes was given to all subjects. An ideal experimental setup would be to have runners running laps, continuously, outdoors, during a sufficiently long period (e.g. 1h) and each lap let them pass through the measurement zone. The running track resembles much more closely real outdoor running in comparison with running on a treadmill, which is still a widely spread method to study running biomechanics.

Another limitation of our study lies in its design. We aimed to assess kinematic and impact intensity differences between runners with different IFCPs and therefore we used a between-subject approach. As such, the observed relations between kinematics and impact intensity could only be shown for existing inter-subject kinematic differences. E.g. It has been shown that a within-subject increase in step frequency can be related to a decrease in impact intensity (26). As we found no difference in step frequency between the different IFCPs we also found no relationship between VILR and step frequency.

Another limitation is that in our studies we have used VILR and the peak of the calculated high frequent VGRF component as the main variables to describe impact intensity. The relation between running kinematics or IFCP and other impact intensity measures such as peak tibial acceleration which is often used for on-line biofeedback in gait retraining studies should be confirmed.

4. FUTURE RESEARCH PERSPECTIVES

Although we gained important new insights into the determination of IFCP, the influence of running speed on IFCP, the relation between IFCP and impact intensity and impact related kinematics, still some important questions remain. Future IFCP-related studies should try to answer the following questions.

4.1. What are the individual determinants for a certain IFCP?

As the different IFCPs show kinematic and joint work differences it might be assumed that anthropometric, morphological or mechanical gait characteristics could determine why a runner obtains a certain IFCP. It has already been demonstrated that IFFC runners have a greater ankle plantar flexion strength than IRFC runners (32). Also Miller *et al.* (34) have stated that the functional strength of the superficial layer intrinsic foot muscles supporting the longitudinal arch could better sustain an IFFC, as a stiffer arch could be seen as a better lever. Future research should determine if other factors such as e.g. arch height, ankle range of motion, Achilles tendon moment arm, … might be related to a certain IFCP. Moreover, in the first study we have shown that some subjects show an inter-limb IFCP asymmetry. Future research should determine possible causes for this asymmetry. Maybe leg dominance or leg length discrepancies could influence such an IFCP asymmetry.

4.2. Why does IFCP change with increasing speed?

We observed that some runners change towards a more anterior IFCP when running faster. However, it is still unclear why these changes occur and why not all runners perform such IFCP-shifts. Several possible hypothesis can be formulated. For faster running, stride frequency needs to increase and contact time needs to decrease (10, 45). Farley *et al.* (20) have shown that greater stride frequencies are achieved with greater leg stiffness. Arampatzis *et al.* (4) have shown that when running faster, mainly an increase in knee stiffness accounts for the increased leg stiffness. We found that IMFC are characterized by a higher leg and knee stiffness when compared with Typical IRFC. As such, shifting towards a more anterior IFCP, e.g. from IRFC to IMFC, might facilitate the increase in leg stiffness which is needed when running faster. Also, as joint stiffness differs between the different IFCP, IFCP-shifting might be a way to redistribute the total leg stiffness over the different joints. Moreover, when running faster, the impact intensity increases (36). We have shown that IFCP is related to impact intensity, as such IFCP-shifting might also be a way to limit the increase in impact intensity that is associated with faster running. Future research should compare the effect of running speed on the above-mentioned variables between runners performing a speed induced IFCP-shift and runners that do not perform an IFCP-shift. Also a within-subject comparison could be made between allowing runners to perform an IFCP-shift and specifically instructing runners not to perform an IFCP shift.

4.3. What is the within-subject relation between running kinematics and impact intensity?

In our second study we have shown the relation between some running kinematics and impact intensity. However, due to the design of our study, only the relationship between inter-subject differing kinematics and inter-subject differing impact intensity could be shown. Future research needs to confirm these relations, and possibly also find other relations between running kinematics and impact intensity, in a within-subject design (such as e.g. a gait retraining study). Some studies have already conducted gait retraining studies aiming at an impact reduction. Some researchers found that after gait retraining, based on real-time feedback on peak tibial accelerations, subjects achieved to lower the impact intensity (15). A primary kinematic strategy was to increase the ankle plantar flexion angle at initial contact, or changing from an IRFC to an IMFC. Other researchers instructed runners to run with an IMFC in order to reduce impact intensity (23). If the only feedback on running style would be done based on foot and/or ankle kinematics, the risk exists of going through or even ending up with an Atypical IRFC instead of an IMFC and thus inducing higher VILR, opposite to what would have been intended. Without specific high speed kinematic and/or plantar pressure measurements these two IFCP are hard to discern as they show resembling global and distal kinematics. There is a need for gait retraining studies that incorporate Atypical IRFC in their analysis and check retention. Also other kinematic changes might induce a reduction in impact intensity. Based on our second study we hypothesize that e.g. an increase in contact time and increase in posterior foot inclination (~more pronounced IRFC) might also reduce the impact intensity. Future research should aim to identify the within-subject kinematic impact reducing strategies.

4.4. Can IFCP-specific shoe design cushion impact intensity?

Shorten *et al.* (43) have shown that passive cushioning by the shoe midsole can influence the impact intensity. However, they have also shown that the effect of shoe cushioning should be evaluated by assessing the peak of the high frequency (>10 Hz) force component and not by the magnitude of the total VGRF ‘impact’ peak, as this peak also contains low frequent, non-impact, components. In our third study we have shown that different IFCPs might benefit from passive cushioning in different zones of the shoe. It has also been shown that shoe design, especially heel-toe offset, can influence IFCP. Therefore, future research should assess the influence of IFCP-specific cushioning footwear on impact intensity and running kinematics.

4.5. Is IFCP related to running performance?

Based on the higher prevalence of IMFC and IFFC in elite runners (25, 27, 29) some researchers have hypothesized a performance benefit with these IFCPs. However, in our first study we suggested that the greater percentages of IMFC and IFFC in elite runners might be a consequence of their faster running speeds rather than these IFCPs being beneficial for performance. Some studies showed that an IMFC or IFFC was more economical than an IRFC (41), while others found that an IRFC was more economical than an IMFC (37, 48). Others found no difference in running economy between different strike patterns (24, 33, 38). As we found in our first study, some runners perform a shift from IRFC to IMFC or IFFC when running faster, we hypothesize a possible interaction between IFCP and running speed and economy. Therefore, future research should assess the differences in running economy between the different IFCPs, when running at different velocities.

4.6. What are biomechanical predictors for running related injuries?

The list of biomechanical variables for which evidence exists, derived from well-designed prospective studies, that they relate to an increased risk for running related lower limb injuries is very limited (9, 14, 35). Many studies have used retrospective or cross-sectional designs and as such no real causality can be determined. This is also the case for the relation between impact intensity and stress fracture susceptibility. There is a need for well-designed prospective studies aiming at determining the biomechanical, anatomical and training related risk factors for running related injuries. Also the possible mechanisms behind these relations should be determined. We recognize that performing such studies is very challenging due to the often multifactorial and individually specific nature of running related injuries.

5. GENERAL CONCLUSION

We have introduced a refined SI method to determine IFCP, which allows to discern Typical and Atypical IRFC, IMFC and IFFC. Based on this method, we have determined the influence of running speed on IFCP, the kinematic and impact intensity differences, the difference in impact intensity distribution under the foot and the joint loading differences between the different IFCPs.

- **Most runners perform an IRFC**. However, **IFCP is influenced by speed** as some subjects changed towards a more anterior located (IMFC or IFFC) IFCP with increasing speed.
- Typical IRFC, Atypical IRFC and IMFC are **considerably different running styles** based on differences in kinematics and impact intensity.
- **Different IFCPs use different impact reducing kinematic strategies**. Typical IRFC use an initial ankle plantarflexion and the cushioning properties of the heel fat pad and heel part of the shoe while IMFC use an initial ankle dorsiflexion.
- **IFCP is related to the impact intensity and the spatial distribution of the impact intensity** over the different foot zones. IMFC were shown to have the lowest impact intensity, while Atypical IRFC were shown to have the highest impact intensity. This impact intensity is mainly situated under the rear- and midfoot for the Typical IRFC, under the midfoot for the Atypical IRFC and under the mid- and forefoot for the IMFC.
- **IFCP is related to loading of the extensor muscles crossing ankle and knee.** Running with a Typical IRFC shows the highest eccentric extensor power at the knee, while running with an IMFC showed the highest eccentric plantar flexion power at the ankle joint.

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LIST OF PUBLICATIONS

A1, Accepted

Breine B, Malcolm P, Frederick EC, De Clercq D. Relationship between Running Speed and Initial Foot Contact Patterns. *Med Sci Sports Exerc.* 2014;46(8):1595-603.

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A1, Submitted, under review

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Conferences, first author

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Malcolm P, Breine B, Frederick EC, Cheung J, De Clercq D. Correlations between strike index and 5,000 and 10,000 m performance in male runners. *Footwear Science*. 2013*;* 5(suppl. 1), p.S100-S101.

APPENDICES

APPENDIX 1: TEST FOR NORMAL DISTRIBUTION OF SELECTED VARIABLES

In the three studies described in this thesis, parametric statistical analyses were used. In order to justify these analyses, we tested if the selected variables were normally distributed within the different IFCP groups that were compared. For this purpose, Shapiro-Wilk's normality tests were conducted in SPSS 22.

STUDY 1: RUNNING SPEED AND IFCP

In our first study, we compared contact time and VILR between different IFCP groups, for both left and right foot contacts and over 4 different speed conditions. Table 1 provides an overview of the results of the normality test for contact and VILR within the different IFCP groups, per foot side and per speed condition.

Table 1: *Results of the Saphiro-Wilk's normality test for contact time and VILR within the different IFCP subgroups, per foot side, per running speed.*

		Contact time					VILR			
Speed condition	**Foot side**	**Typical IRFC**	**IMFC**	**IFFC**	**Atypical IRFC**		**Typical IRFC**	**IMFC**	**IFFC**	**Atypical IRFC**
3.2 m·s^{-1}	LE	√	√	N.A.	√		√	√	N.A.	√
	RI	√	√	N.A.	√		√	√	N.A.	√
4.1 m·s^{-1}	LE	√	√	N.A.	√		√	√	N.A.	x
	RI	√	√	√	√		√	√	√	√
5.1 m·s^{-1}	LE	√	√	√	√		x	√	√	√
	RI	√	√	√	√		√	√	√	√
6.2 m·s^{-1}	LE	√	√	√	√		x	√	√	√
	RI	√	√	√	√		√	√	√	√

√ variable considered normally distributed within this subgroup.
x variable considered not normally distributed within this subgroup.
N.A. too little subjects to test for normal distribution.

Since the majority of the variables within the different IFCP subgroups (per speed and per foot side) showed a normal distribution, the use of parametric statistics is justified. However, since not all subgroups of variables showed a normal distribution, we acknowledge that for these variables this might have influenced the results from the statistical analysis.

STUDY 2: IFCP KINEMATICS AND IMPACT LOADING RATE

In the second study we compared 40 kinematic, GRF and spring mass model variables between three IFCP groups (Typical IRFC vs Atypical IRFC vs IMFC). Table 2 provides an overview of the variables that were found not be normally distributed within the different IFCP groups.

Table 2: *Overview of the selected variables within the different IFCP groups that are considered as not normally distributed.*

Typical IRFC	Atypical IRFC	IMFC
- time of maximum knee flexion - time of maximum ankle dorsiflexion - time of maximal thigh posterior inclination - forefoot eversion at initial contact - time of maximal ankle eversion - initial ankle dorsiflexion range of motion - initial ankle dorsiflexion joint stiffness	- time of VILR - time of maximal rearfoot eversion - knee flexion range of motion	- leg posterior inclination at initial contact - ankle plantar flexion at take-off - forefoot eversion at intial contact

Since the majority of the variables within the different IFCP subgroups showed a normal distribution, the use of parametric statistics is justified. However, since not all subgroups of variables showed a normal distribution, we acknowledge that for these variables this might have influenced the results from the statistical analysis. However, we used ANOVA analyses with post-hoc Bonferroni correction and it has been stated that ANOVA analyses are robust statistical tests. This means that they tolerate violations against its normality assumptions rather well (Glass 1972, Harwell 1992, Lix 1996).

STUDY 3: SPATIAL DISTRIBIUTION OF IMPACT INTENSITY AND IFCP

In the third study of this thesis we compared VILR and the peak of the high frequency vertical GRF component (HI-GRF) within 4 different foot zones between the different IFCP groups (Typical IRFC vs Atypical IRFC vs IMFC). Table 3 provides an overview of the variables that were found not be normally distributed within the different IFCP groups.

Table 3: *Overview of the selected variables within the different IFCP groups that are considered as not normally distributed.*

Typical IRFC	Atypical IRFC	IMFC
- HI-VGRF medial rearfoot zone - HI-VGRF forefoot zone - VILR medial rearfoot zone	/	HI-VGRF forefoot zone

Since the majority of the variables within the different IFCP subgroups showed a normal distribution, the use of parametric statistics is justified. However, since not all subgroups of variables showed a normal distribution, we acknowledge that for these variables this might have influenced the results from the statistical analysis. However, we used ANOVA analyses with post-hoc Bonferroni correction and it has been stated that ANOVA analyses are robust statistical tests. This means that they tolerate violations against its normality assumptions rather well (Glass 1972, Harwell 1992, Lix 1996).

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APPENDIX 2: DESCRIPTION OF THE KINEMATIC MODEL IN STUDY 2 AND 3

Marker positions

The following markers locations were used:

ME1_ = medial side of metatarsophalangeal joint I

M23_ = superior side of the foot between metatarsophalangeal joint II & III

ME5_ = medial aspect metatarsophalangeal joint V

CAL_DM = distal medial aspect of calcaneus

CAL_PM = proximal medial aspect of calcaneus

CAL_PC = dorsal aspect of calcaneus

CAL_DL = distal lateral aspect of calcaneus

CAL_PL = proximal lateral aspect of calcaneus

MAL_M = most protrusive part of medial malleolus

MAL_L = most protrusive part of lateral malleolus

SHN_DM = distal medial part of shank plate

SHN_DL = distal lateral part of shank plate

SHN_PM = proximal medial part of shank plate

SHN_PL = proximal lateral part of shank plate

KNE_M = between medial condyles of tibia & femur

KNE_L = between lateral condyles of tibia & femur

THG_DM = distal medial part of thigh plate

THG_DL= distal lateral part of thigh plate

THG_PM = proximal medial part of thigh plate

THG_PL = proximal lateral part of thigh plate

TRO_ = most protrusive part of trochanter major of femur

Segment coordinate system definitions

The origin of the **thigh segment** coordinate system is centered between the trochanter maior marker and the landmark centered between the left and right trochanter maior markers. The y-axis of the thigh is drawn as the extension from the line between the origin and the center of the medial and lateral knee markers and oriented cranially. The x-axis is drawn orthogonally on the longitudinal axis (y-axis) and the mean orientation of the projection of the lines between the trochanter and the knee markers on a perpendicular plane with the y-axis. The x-axis is oriented anteriorly. The z-axis is drawn orthogonal to the x-y plane and oriented to the right. The thigh is tracked by 4 markers mounted on a semi rigid plate taped halfway on the thigh.

The origin of the **shank segment** coordinate system is centered between the knee markers. The y-axis of the shank is drawn as the extension from the line between the center of the malleoli markers and the center of the knee markers and oriented cranially. The x-axis is drawn orthogonally on the longitudinal axis and the mean orientation of the projection of the lines between the knee markers and the malleoli markers on a perpendicular plane with the y-axis. The x-axis is oriented anteriorly. The z-axis is drawn orthogonal to the (x-y) plane and oriented to the right. The shank is tracked by 4 markers on a plate halfway on the shank.

The origin of the **rearfoot segment** coordinate system is set at the dorsal calcaneus marker. The x-axis is drawn between the origin and the center of the first and fifth metatarsal markers (47% from medial marker) and oriented anteriorly. The z-axis is drawn orthogonal to the x-axis and parallel with the line through the metatarsal markers and oriented to the right. The y-axis is drawn orthogonal to (x-y) plane and oriented cranially. The rearfoot is tracked by the four calcaneus markers.

For the inverse dynamics analysis of which the results are presented in the discussion. For these analyses the following **foot segment** was used instead of the rearfoot segment described above. The origin of the foot segment is set in the middle between the two malleolus markers. The x-axis is drawn between the origin and the center of the first and fifth metatarsal markers and oriented anteriorly. The z-axis is drawn orthogonal to the x-axis and parallel with the line through the malleolus markers and oriented to the right. The y-axis is drawn orthogonal to (x-y) plane and oriented cranially. The foot segment is tracked by the four calcaneus markers.

All joint angles and joint moments were calculated using a ZXY cardan sequence (Z = sagittal plane rotations, X= frontal plane rotations, Y= transverse plane rotations) with the proximal segment as reference segment.

APPENDIX 3: EXAMPLE COP CURVES FROM FORCE PLATE DATA

The figure below shows the COP trajectories of 3 representative left foot contacts at 3.2 $m \cdot s^{-1}$ trials from one subject (own data). These COP trajectories were calculated from the force plate force and moment signals. This figure shows that COP calculations with low GRF are not reliable. The COP position is expressed relative to foot length.

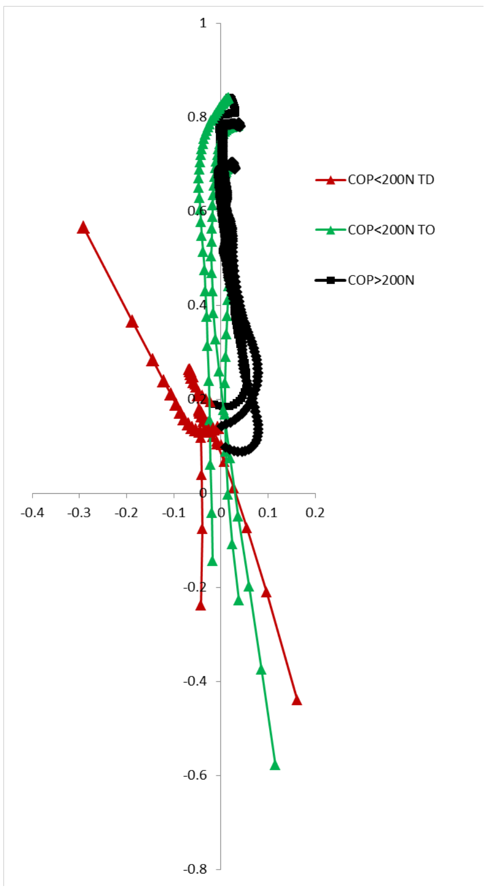


Figure: *Example COP trajectories from 3 representative trials. The green and red trajectories show the COP trajectory with GRFs below 200N at initial contact (red) and during push-off (green).The vertical axis is the anterio-posterior COP position expressed in relative foot length. The x-axis is the medio-lateral COP position expressed in relative foot length.*

In our studies we have used an AMTI force plate. With these force plates the formulas for calculating the COP location (x,y,0) relative to the force plate's origin are presented below. The COP can be calculated from the moment caused by the ground reaction force about the true origin (M_x, M_y, M_z), the ground reaction force (F_x, F_y, F_z), and the location of the true origin (a,b,c). The matching of the force plate's internal coordinate system with the kinematic coordinate system can be done in visual 3D. As the vertical GRF component F_z is in the denominator of the formula, small errors in the measurement of low values can produce large deviations in the calculated COP position. Therefore, COP positions derived from force plate are only reliable when a certain Fz threshold is reached.

(reference: http://www.kwon3d.com/theory/grf/cop.html)

$$COPx = -\frac{M_y + cF_x}{F_z} + a$$

$$COPy = -\frac{M_x + cF_y}{F_z} + b$$

APPENDIX 4: EXAMPLE INDIVIDUAL JOINT MOMENT AND JOINT POWER CURVES

Joint angles and moments were calculated with a standard inverse dynamics approach with Cardan sequence. Joint power of the knee and ankle (mainly in the sagittal plane) was calculated as the product of sagittal plane joint velocity and sagittal plane joint moment. The kinematic model is described in appendix 2. Ground reaction forces were filtered with a Butterworth low pass filter with a cutoff frequency of 80 Hz and kinematic data with a cutoff frequency of 20 Hz. To check if our methods did not introduce measurement artefacts (e.g. unexpected or unreal peaks in the calculated joint moments) we studied the individual curves. Below are the knee and ankle joint moment and power curves from all trials from 4 selected subjects. No measurement artefacts are shown in these curves, and these curves match joint moment and power curves reported in the literature (e.g. Williams *et al.* 2000)

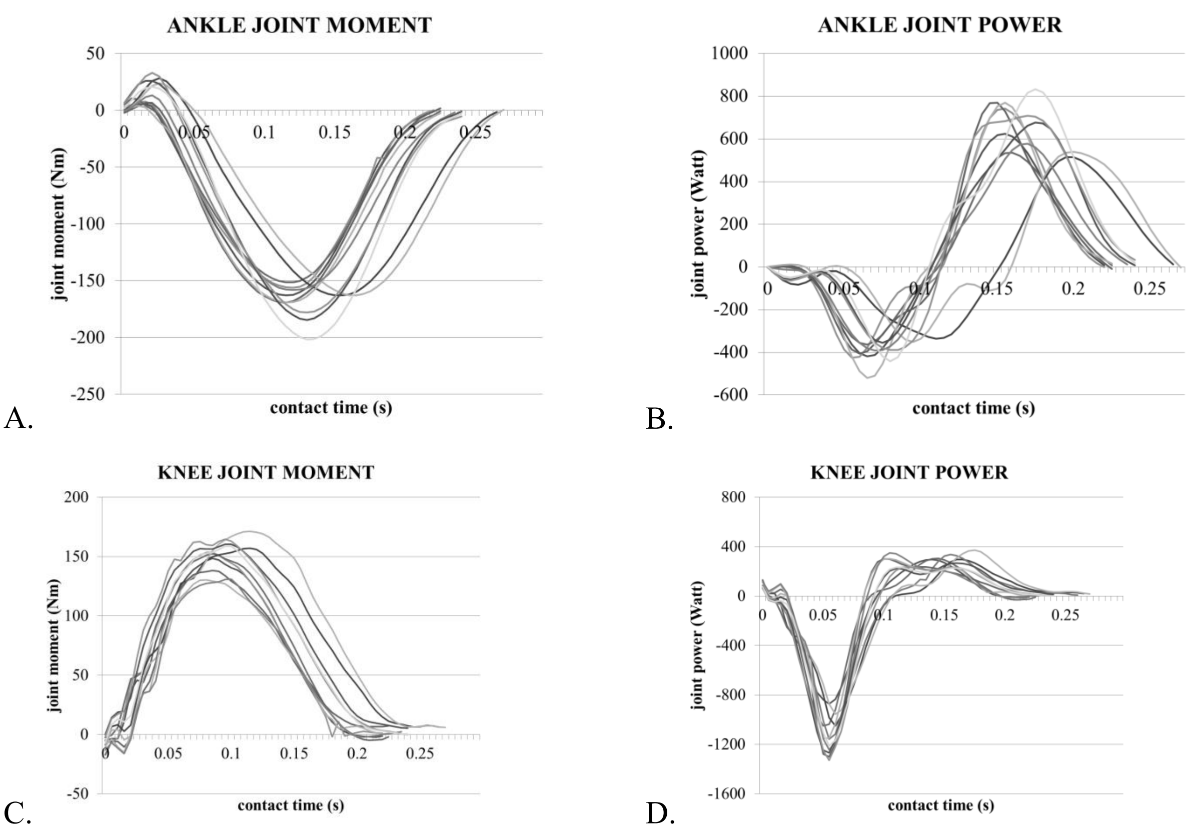


Figure: *ankle joint moment (A) and power (B) and knee joint moment (C) and power (D) from representative left foot contact trials from 4 subjects running at 3·m•s^{-1}.*

Reference

Williams DS III, McClay IS, Manal KT. Lower extremity mechanics in runners with a converted forefoot strike. *J. Appl. Biomech.* 2000;16:210-218.

APPENDIX 5: THEORETICAL CONSIDERATIONS ON THE ESTIMATED ERROR IN COP CALCULATION FROM FORCE PLATE OR PLANTAR PRESSURE MEASUREMENTS

In Appendix 3 we have elaborated on why COP calculations at initial foot contact, derived from force plate data are not reliable. In this Appendix we provide some theoretical considerations why COP data derived from plantar pressure measurements, especially at initial foot contact are more reliable. The figure shown in Appendix 3 shows initial COP positions outside the foot which are due to the unreliable COP determination when GRFs are very low, which is the case at initial foot contact. The figure below shows example COP trajectories, depicted onto a plantar pressure foot printout, derived from plantar pressure measurements (Rs Scan, 2m footscan).

Initial foot contact | **Total foot contact maximum pressure image**

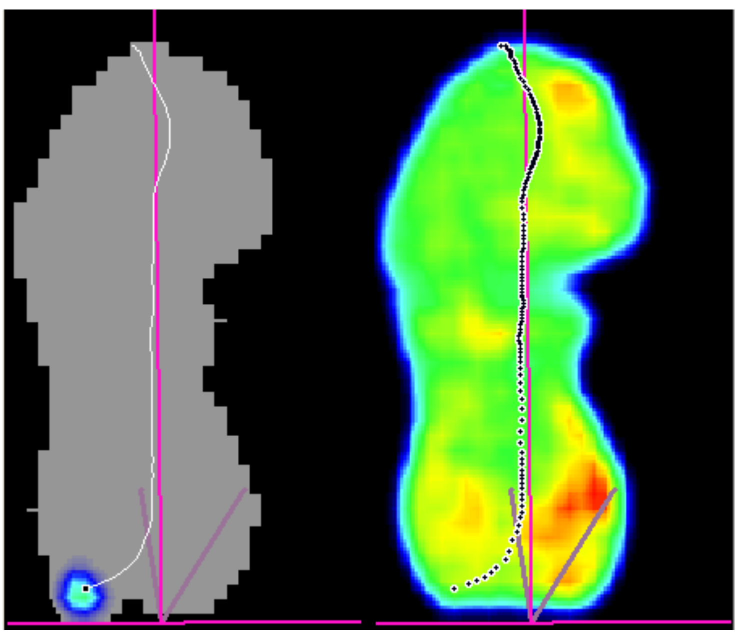


Figure: *Example COP trajectory, derived from a plantar pressure measurement. The left footprint shows the activated measurement cells at initial foot contact. The left footprint shows the composed maximum pressure image. A red color indicates high pressure and green color indicates a low pressure.*

The 2m footscan ® plantar pressure measurement plate consists of a 256*64 matrix of resistive sensors with a size of 0.5088*0.762 cm and a measurement threshold of 0.27 N/cm². At initial contact only very few sensors are activated. In the example above only 2 sensors are activated.

As such the estimated error on the calculated COP location is very small. Also, with such a system initial COP locations outside of the plantar footprint, as are sometimes the case with force plate measurements (appendix 3), do not occur.

To provide an estimation of the uncertainty of the calculation of the initial COP position we calculated the propagation of uncertainty of a function (COP location) with multiple independent variables (amount of pressure per sensor (p_i), location of the local center of pressure on the sensor (x_i)) based on some reasonable assumptions. The following applies for both COP medio-lateral and the COP anterior-posterior position calculations. As in our studies we have used the COP location for the calculation of a strike index the following example will be applied to the calculation of the anterior-posterior COP position.

The general **formula for the propagation of uncertainty** of a function (COP location calculated from x_i and p_i) with multiple variables is:

$$(\delta f(u_i))^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial u_i}\right)^2 (\delta u_i)^2$$

When $f = COP\ calculation = \frac{\sum_{i=1}^{n} p_i x_i}{\sum_{i=1}^{n} p_i}$

$n = number\ of\ activated\ sensors$

$p_i = the\ partial\ pressures\ measured\ per\ sensor$

$x_i = the\ anterior - posterior\ location\ of\ the\ local\ center\ of\ pressure\ per\ sensor$

$u_i = x_1, \ldots, x_n, p_1, \ldots, p_n$

$\partial\ indicates\ a\ partial\ differentiation$

$\delta\ indicates\ uncertainty/error$

Worked out for the COP calculation formula f:

partial differentiation of f to x_i:

$$\frac{\partial f}{\partial x_i} = \frac{p_i}{\sum p_i}$$

Partial differentiation of f to p_i:

$$\frac{\partial f}{\partial p_i} = \frac{x_i.\sum p_i - \sum p_i.x_i}{(\sum p_i)^2}$$

$$antpost\ COP\ location = \frac{\sum p_i.x_i}{\sum p_i}$$

$$\frac{\partial f}{\partial p_i} = \frac{x_i - antpost\ COP\ location}{\sum p_i}$$

The **propagation of the uncertainty** of the calculation the COP antpost position calculation with n active sensors can then be described as:

$$(\delta f(u_i))^2 = \sum_{i=1}^{n}\left[\left(\frac{p_i}{\sum p_i}\right)^2.(\delta x_i)^2\right] + \sum_{i=1}^{n}\left[\left(\frac{x_i - antpost\ COP\ location}{\sum p_i}\right)^2.(\delta p_i)^2\right]$$

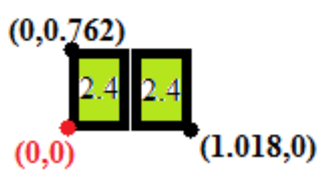
We can now calculate the propagation of uncertainty based on the following **assumptions**:

$\delta x_i =$ 4mm; (note: sensor length of 7.62 mm)

$\delta p_i =$ 0.6 N/sensor; (note: AD conversion quantization steps of 0.3 N/sensor)

Worked out for the aforementioned **example**:

At **initial contact**, 2 sensors were activated (in the sensor, the N per sensor is shown). For ease of calculation the origin of the COP coordinate system is taken at the left bottom corner of these 2 sensors.

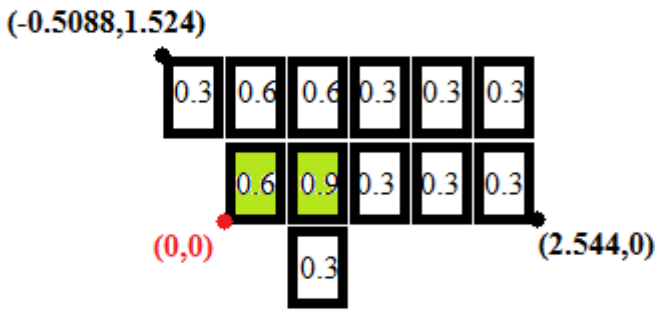


In this example the calculation COP location is at (0.5088,0.381) The calculated propagation of uncertainty of the anterior posterior COP position using the derived formula, expressed in mm is:

$$\delta f_{ui} = \sqrt{\left(\frac{2.4}{4.8}\right)^2.4^2 + \left(\frac{2.4}{4.8}\right)^2.4^2 + \left(\frac{0}{4.8}\right)^2.0.6^2 + \left(\frac{0}{4.8}\right)^2.0.6^2}$$

$$\delta f_{ui} = 2.8\ mm$$

Immediately following initial contact (0.002s later), 12 sensors were activated (in the sensor, the N per sensor is shown). The initially activated sensors are highlighted.



In this example the calculation COP location is at (0.943,0.695)

The calculated propagation of uncertainty of the anterior posterior COP position using the derived formula, expressed in mm is:

$$\delta f_{ui} = 1.3\ mm$$

These calculations, based on reasonable assumptions show that the calculation of the initial COP position from a footscan ® plantar pressure measurement system are more reliable than the initial calculation of COP positions based on force plate data (Appendix 3).

APPENDIX 6: LIST OF ABBREVIATIONS

Initial foot contact pattern	IFCP
Initial rearfoot contact pattern	IRFC
Initial midfoot contact pattern	IMFC
Initial forefoot contact pattern	IFCC
Center of pressure	COP
Strike index	SI
Leg stiffness	k_{leg}
Vertical stiffness	k_{vert}
Joint stiffness	k_{joint}
Ankle stiffness	k_{ankle}
Knee stiffness	k_{knee}
Ground reaction force	GRF
Vertical component of the ground reaction force	VGRF
Maximal vertical ground reaction force	$VGRF_{max}$
High frequency component (>10 Hz) of the vertical ground reaction force	HI-VGRF
Leg compression	ΔL
Vertical oscillation	Δy
Stride length	SL
Stride frequency	SF
Contact time	CT
Flight time	FT
Peak vertical instantaneous loading rate of the GRF	VILR
Average loading rate	VALR
Peak tibial acceleration	PTA
95% confidence interval	CI

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Bastiaan

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