APPENDIX

SKILLED FOR LIFE

Towards prevention of overuse lower limb injury with a smart wearable for military use

Master graduation thesis

by Laura Ahsmann

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Appendix 1.

ORIGINAL PROJECT BRIEF

Throughout the project, the initially written project brief has evolved and after several iterations on the study goals, the final assignment was defined. The initial project brief was written on September 27th, at the start of my graduation project:

Project brief
The aim of this project is to develop a design proposal (with proof of concept) for a wearable measurement system for military units to be used during training programs, that is able to provide predictors for most occurring OLLI's in military setting.

For this aim to be accomplished successfully, research should be done on (1) proven predictors of common bone and musculoskeletal injuries and how to measure them, (2) the military network of stakeholders and how data should be used within a training program and (3) currently available measurement systems on the market for the lower limbs. This research will be done by means of literature studies and expert consultations.

After the research phase, a product concept will be developed, which takes into account (1) the standard military footwear, (2) the types and locations of sensors to measure required predictors, (3) the effect of different ground surfaces and the damping of the shoes on sensor data, (4) the materials and sizes for the product, (5) the types of data acquired and presented and finally (6) the look, feel and use of the product.

Throughout the design phase, prototypes will be made to test their working principle. A final prototype of the product concept should be able to show the proposed product's full working principle including (simplified) data processing.

Lastly, an indication of the production process steps and the cost price per unit or batch of units will be assessed.

Assignment
I am going to design a wearable footwear product that enables the military to collect high amount of detailed and relevant data points about gait biomechanics of recruits during military training, to be able to predict and prevent injuries caused by high training load.

The solution will be explored in the field of an in-shoe wearable, integrated with sensors and a software system that translates complex data into a usable interface. For the product to be successful, research should be done on biomechanical and anthropometric predictors of injury and the user group (military).

Appendix 2.

GLOSSARY

Gait = Manner of walking
PE = Physical Exercise
In-loco = In the place of normal usage (this case the field), rather than in the laboratory
RT- PSM = Real Time Physiological Status Monitoring

OLLI = Overuse Lower Limb Injury
RRI = Running Related Injury
MSST = Medial Tibial Stress Syndrome / Shin splints
TSF = Tibial Stress Fractures
ITBS = Iliotibial band syndrome
OA = osteoarthritis

FFP = Footfall pattern
dROM = dynamic Range of Motion
vGRF = vertical Ground Reaction Force
RFEV = Rear Foot Eversion
FAH = Foot arch height
FAI = Foot arch index
PTS = Peak tibial shock / Peak positive tibial acceleration

MP = Midfoot pronation
iCoP = Initial centre of pressure
VIP = Vertical impact peak
VLR = Vertical loading rate
FB = Foot balance
TPHR = Time to peak heel rotation
TA = Tibial alignment
SA = Subtalar alignment
TFM = Tibial free moment

AMO = Algemene Militaire Opleiding (Dutch basic military training)
DMO = Defensie Materieel Organisatie
TGTF = Trainings Geneeskunde & Trainings Fysiologie
KPU = Kleding en Persoonsgebonden Uitrusting

ROI = Regions of Interest
ROI-TIME = Region-Time Curves
COP = Centre of Pressure
IMAGE = Pressure Pattern Images
FRS = Force Resistive Sensor

MH = Medial heel
LH = Lateral heel
M1-M5 = Metatarsal 1 - Metatarsal 5
T1 = Hallux

Appendix 3.

LITERATURE STUDY

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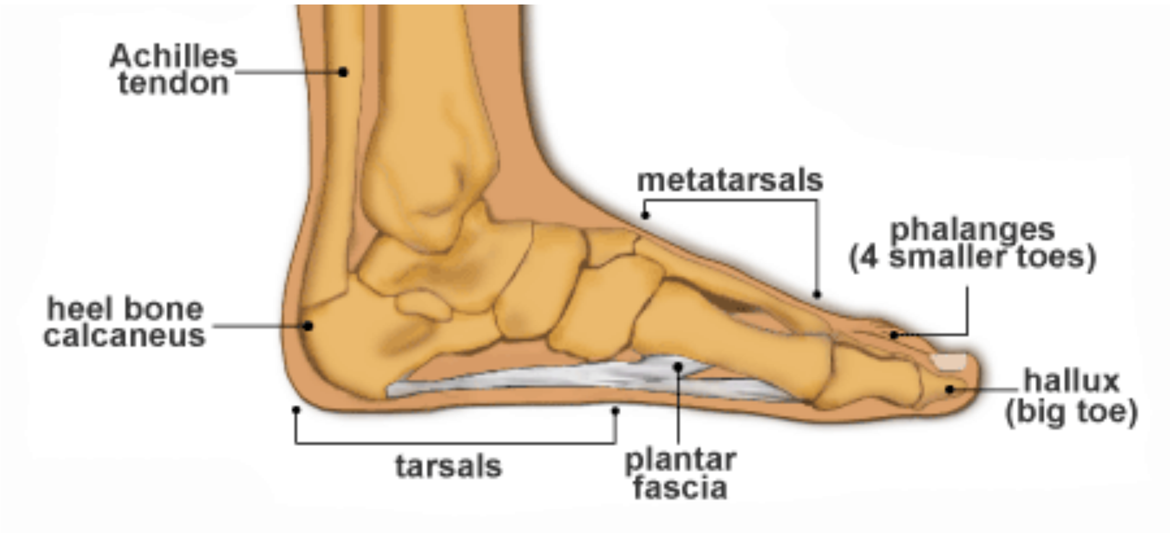


Figure A3.1 - Foot anatomy (Aid my Bursitis, n.d.)

Figure A3.2 - Army boot parts

1. INTRODUCTION (PROBLEM DEFINITION)

Military trainings are often very long and intensive. On top of that, they include a lot of heavy, repetitive load. Repetitive load is continuously causing micro traumas on sensitive muscle and tendon fiber areas. Without early intervention, this will result in overuse injury, which is happening to 25 to 82% of military recruits (Franklyn-Miller et al, 2014). The lower extremities cover the largest share of injury cases with 39% of the total, as recorded in the Department of Defence (Hauret, 2010).

Investigating intrinsic risk factors from foot function has been proven to be able to predict potential injury cases (Franklyn-Miller et al, 2014; Friedl, 2018; Daoud, 2012; Cowan, 1996; Milner et al, 2006; Sharma, 2007; Verrelst et al, 2018; Strauss et al, 2011). Preventing injury would be beneficial for not only the individual recruit (5 steps to Reduce.., n.d.), but also the efficiency of the entire military unit, the duty healthcare would be less occupied and it will eventually cut costs. Training of a recruit costs around 10.000 euro (D. van Tiggelen, personal communication, September 24, 2019). Divided by the percentage of dropouts per year accumulates to a significant financial hit for the military, roughly estimated at €2300 per recruit). Besides that, after enduring an injury, the chance of sustaining another injury increases (Andersen et al, 2016; Meeuwisse, 1994), which makes it even more effective to prevent the first one from happening.

Until now, the majority of kinetic and kinematic studies has been performed in a laboratory setting. A lab setting brings advantages such as enough space for a large setup, wires and computers, full attention from the participant, and privacy. But relocating is a long and expensive operation, according to D. van Tiggelen (personal communication, September 24, 2019) and literature (Aminian, 2002). A lab setup also brings several disadvantages to research outcome. A single force plate evokes "platform targeting" (Mann, 2016), allows for only one footfall per trial and requires barefoot running, which does not compare to shod running (Rothchild, 2015). A single data collection moment doesn't account for unexpected - involuntary - changes in kinematics (Verrelst, 2018) or effects of fatigue (Grech et al, 2016) throughout the study period. Lastly, the contextual variables such as different terrain types are not included in laboratory studies (Lacirignola, 2017).

If data is needed from every individual military trainee, these tests periods will take months. Using a treadmill, some of these drawbacks could be excluded, but it would require expensive, complex test apparatus and even a treadmill has shown to affect the natural running behavior (Chambon, 2015).

The market currently offers a range of wearable RT- PSM (Real-time physiological status monitoring) systems for foot measurements. Most of the currently available systems focus on sport-specific measurements (e.g. JOHAN for field sports and Digitsole for running) and include private software systems (apps) to be used by individual consumers. Other products are simply over-engineered with the research-purpose to measure as many parameters as possible to be able to find specific correlations. They can be very expensive and mostly not useful for military trainees (Veenstra & Friedl, 2018).

The potential for RT-PSM systems lies in early detection of injury risk. With either orthopaedic interventions (Schrijver, personal communication, September, 2019) or practical gait retraining (Sharma, 2014; Zimmerman et al, 2018), the risk for injury can be reduced with 60%.

As this specific target group shows high demand for a solution in injury prevention, as mentioned above, it makes a good challenge to combine available data and developments in the industry with the requirements from a specific user group to create a valuable product. The other way around, data that will be collected from this (relatively large) target group, could be used for research on injuries in other user groups, but also for the purpose of rehabilitation monitoring after surgery, defining proper fit of external prosthesis and orthosis, fall-risk assessment of elderly or finding appropriate assistive devices (Aminian, 2002).

This report outlines a literature review on the topic of injury prevention in the military, based on biomechanical parameters that can be measured from under the foot. The research question of this project is:

"How can we reduce incidence of lower limb overuse injury among military recruits during initial training programs using a wearable RT-PMS?

2. WALKING BIOMECHANICS

2.1 The human gait

The human gait cycle consists of a stance phase and a swing phase (Figure 3). The stance phase is divided in four sub-categories (Torricelli et al, 2016) starting with (i) the loading response (or heel strike) where both feet are in contact with the ground, (ii) the mid stance, which starts at contralateral toe-off and ends with heel-rise, (iii) the terminal stance, which ends at initial contact of the contralateral limb and (iv) the pre-swing, where both feet are on the ground and which ends the phase with toe-off. The stance phase covers around 60% of the cycle of which 20% with double limb contact and 40% single leg support per leg. When walking speed increases, the single leg support lengthens until the full gait consists of single leg support (see Figure 3).

2.2 Footfall pattern

We are all different in the way we walk; that is why some people endure an injury for the same physical load where others do not. Footfall pattern (FFP) is one of the main individual differences in a gait cycle; it is the way a person lands at initial floor contact. Generally, there are three types of FFP: a rearfoot (RF), midfoot (MF) and forefoot (FF) FFP (Hamill, 2017). Different

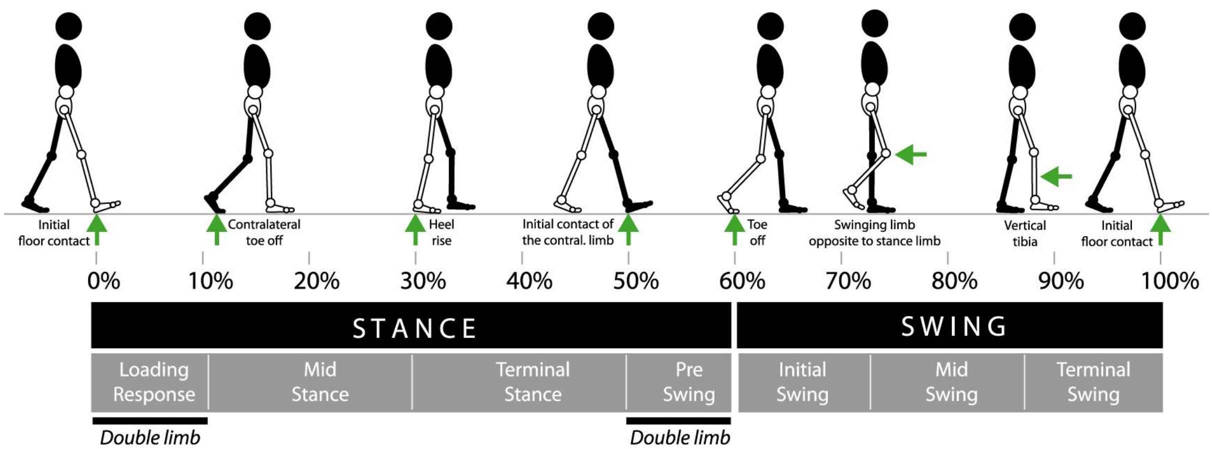


Figure A3.3 - Human Gait Cycle (Torricelli, 2016) studies found different distribution of footfall type ranging from 75%-94% RF, 19%-23% MF and 0%-2% FF (Kerr et al, 1983; Hasegawa et al, 2007; Larson et al, 2011). Not only does the footfall pattern change between individuals, a person could change its own footfall pattern during a walking-running transition or after removing footwear.

The graph in Figure A3.4 shows the rate of Vertical Ground Reaction Force (VGRF) during RF and FF FFP (Hamill, 2017). A large difference can be seen in the presence of an impact peak and an increased loading rate for the RF footfall pattern. This increased loading rate and impact peak are subject to increased injury risk.

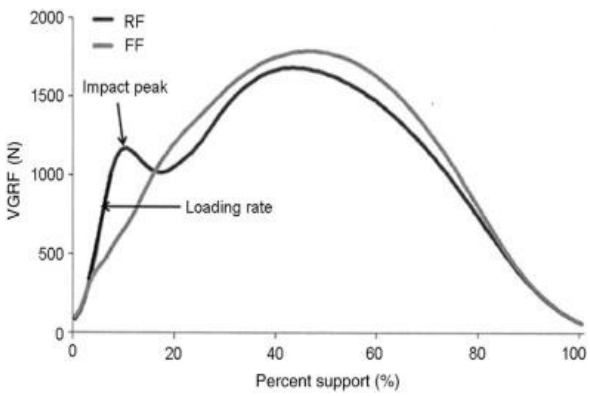


Figure A3.4 - Footfall pattern and vertical Ground Reaction Force (Hamill, 2017)

2.3 Transversal ankle locomotion

Besides the plantar flexion and dorsiflexion motions of the ankle caused by footfall pattern, the ankle also shows eversion and inversion motions during stance. Pronation is a combination of dorsiflexion and eversion of the ankle, while supination is the opposite (Nagano, 2018), see Figure 5. The rate and timing of pronation during stance has impact on the impact loading and guides accommodation of the ground surface (De la cruz, 2014). Floor contact with a supinated ankle results in immediate pronation and accompanying internal tibial rotation (Negano, 2018). Towards foot-flat, the ankle starts to supinate, combined with concentric and eccentric motion. All these factors of gait kinematics influence the weight distribution and Centre of Pressure (CoP) on the sole of the foot. This subject will be further elaborated in paragraph 6.1.

2.4 Cadence

Walking cadence can be seen as a valuable input source for possible risk factors. According to Maj. Prof. D. van Tiggelen (personal communication, September 24, 2019), a low cadence (appr. 150 st/min) with high walking speed causes a larger impact per step. A recruit

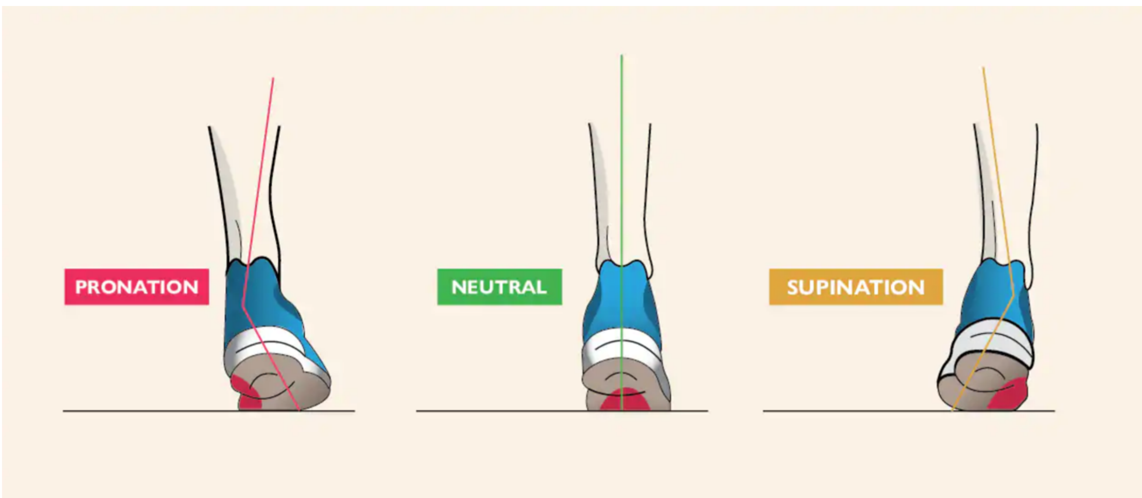


Figure A3.5 - Foot pronation and supination should aim at about 170-180 steps per minute.

3. OVERUSE INJURIES IN PHYSICAL EXERCISE

3.1 What is Overuse injury?

Overuse Lower Limb Injury (OLLI) is a collection-term used to describe injuries caused by overtraining, overexertion, repetitive movement, forceful actions, extreme joint positions and prolonged static positioning (Hauret et al, 2010). OLLI's can occur in many types of physical activity including sports and occupational training, such as the military.

3.2 OLLI's in the military

Military training has proven itself as high injury risk with instances from 25 to 82% (Franklyn-Miller et al, 2014). In the military, trainees perform long, heavy-packed marches. Even though acute trauma might not occur during the march, every step creates a micro-trauma which cumulatively creates large forces on the muscles and ligaments in the lower limbs . Most common OLLI's in the US Department of Defence are categorized as stress fractures, Sprain/strain/rupture and inflammation and pain (respectively counting 6979, 1935 and 256268 instances per year). The lower extremities in general account for about 39% of all injuries recorded in the DoD. Table 1 gives an overview of most occurring OLLI's and their impact on the military.

Table 1 - OLLI incidence and morbidity impact overview

Name	Incidence*	Description	Morbidity impact
Knee	14,7%		
Patellofemoral Pain Syndrome		The knee cap rubs against the thigh bone which causes swelling and pain (aka Runners knee)	Could take weeks to months [5]
Patellar tendinopathy		Overstress of the Patella tendon (aka jumper's knee)	Ranging from 7 days to multiple weeks [5][7]
Iliotibial band syndrome	6,19%	Lateral knee pain (or inflammation) caused by friction of the iliotibial band against the lateral femoral epicondyle [11]	Around 8 +/- 5 days. In chronic cases it might need surgery [11]

Tibia	6%		
Tibial stress fracture	1,39%	Small cracks in the Tibia, causing pain and swelling, especially during activity	85 [10] - 103 days [7]
Medial Tibial Stress Syndrome (Shin splints)	5,67%	Pain in the front and side of the shin	Could take years to recover, for some patients the pain will never really go away [5], might be the most impactful OLLI in military [8], greatest impact in terms of recovery days [10]
Achilles	3,6%		
Achilles tendinopathy	1,47%	Inflammation and fibrous tissue in the Achilles tendon that cause pain, tenderness, redness, joint swelling and creaking	Ranging from 7 days to multiple weeks [5][7]
Foot & ankle	6,8%		
Metatarsal stress fracture	1,24%		Ranging from a few months to 103 days [5][7]
Metatarsalgia / Bursitis		Inflammation or pain in the metatarsal area of the foot caused by overuse or nerve compression [5].	Could take a few months [5]
Plantar fasciitis / heel spurs	0,85%	Inflammation or fibrous tissue that cause pain in the sole of the foot (plantar fascia). In bad cases, the inflammation could lead to heel spurs.	Could take years at worse to recover and might require surgery for heel spurs [5].
Local skin discomfort		Discomfort on the skin tissue caused by friction or too tight shoes	Short, but recurring if not solved.
Sprained ankle	5,02%		

* (% of all recruits) [9][10]

[1] Emedicinehealth, Stress fractures
[2] van Tiggelen, D (2019)
[3] "What are heel-spurs?" (n.d.)
[4] "Preventing injuries in military training", (n.d.)
[5] Schrijver, J. (personal communication, October 3, 2019)
[6] van Rompay (2011)
[7] Kaufman et al (2000)
[8] Sharma (2013)
[9] Van Rompay (2011)
[10] Sharma (2015)
[11] Strauss et al (2011

3.3 Causes of OLLI

There is a number of extrinsic factors that play a role in the attribution of injury. Think about training intensity, mileage, terrain type, load carrying and wearing of military boots (see chapter 5). Blacker et al (2008) and Knapik et al (2001) also proved that fatigue can change mobility patterns and increased biomechanical load subsequently results in injury risk. Surprisingly, most injuries occur in first three weeks (of which the second week highest), even though the intensity is relatively lower than later weeks (Almeida et al, 1999; Sharma, 2015).

Individual intrinsic factors such as age, flexibility, previous injury and somatotype (Figure 6) have also been associated to contribute to injury risk (Meeuwisse, 1994). Not entire an intrinsic factor, but also a significant predictor for injury is habit of smoking (Sharma, 2013), as this factor is associated with impaired microcirculation and tissue repair. Considering this input as a risk factor, the predictability increases with 20%.

This project, however, focuses on intrinsic biomechanical factors. Exactly which intrinsic factors have been studied and their contribution to injury prediction, will be elaborated in chapter 6.

4. THE MILITARY

4.1 Military training

To prepare for combat, military recruits all over the world undergo a basic training program. In the British Army, the Infantry Training Centre Catterick (ITCC) is taken by more than 3500 recruits each year and lasts for a minimum of 26 weeks (Sharma, 2015). The program includes training for aerobic fitness, muscle endurance and strength, resistance training, battle training and loaded marches and is considered to be the toughest training that the British Army offers, with a medical discharge rate of 8%, mostly due to musculoskeletal injury. This number does not only have impact on the individual, but is also bad for morbidity, training time, resources and manning of the entire army (see Table 1).

4.2 The military as a user

Many studies have acknowledged the necessity of injury prevention in the military (Blacker et al, 2008; Kaufman, 2000; Knapik, 2001; Franklyn-Miller et al, 2014; Sharma, 2013; Taanila et al, 2009; van Rompay, 2011). But for an injury prevention tool to be both valuable and useful for this target group, it should be fitting with its extraordinary structure and requirements.

For instance, it should have minimum size, weight and power consumption,

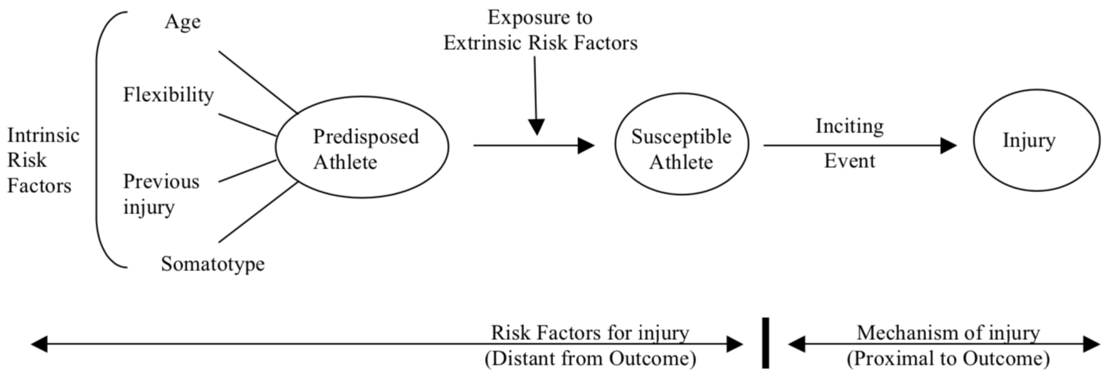


Figure A3.6 - Multifactorial model for Risk exposure (Meeuwisse et al, 1994)

- in case of sensitive information - a secure data communication system, physiological algorithms validated for - and relevant to - military use and user (soldier) demand and acceptance (Veenstra & Friedl, 2017). Relevant is - in this context - for individuals and teams to learn safety limits and optimize workload.

Biomechanical data derived from the insoles should end up with someone who use the information most effectively. A sergeant is closest to the group and could take direct action if needed. However, a sergeant is not responsible for physical wellbeing and might act with different intentions (e.g. finishing the exercise according to planning). A more independent (unbiased) stakeholder are sports instructors and physiotherapists (D. van Tiggelen, personal communication, September 24, 2019). A central rehabilitation centre in the Netherlands is located in Doorn. Physiotherapists there already work with force plates and clinical tests, which makes them the most qualified to deal with measurement data (Staff comm. B. Veenstra, personal communication, October 11, 2019). Data processing and (detailing of) presented data depends on who will eventually interact with the data and should be usable for that particular group (Friedl, 2018).

4.3 Data security and privacy

Security of data communication is mentioned as an important factor by Veenstra & Friedl (2017). The military holds all kinds of sensitive data which can be misused if ended up in the wrong hands. An example of big-data activity monitoring service gone wrong is when Strava - one of the largest fitness tracking apps in the world - shared a heatmap with exercise routes online, revealing the locations of several military bases in Afghanistan and Syria (Hern, 2018). Strava responded to the criticism by suggesting military personnel to opt-out of the heatmap data collection. However, even with this functionality turned off, the Strava website also shares segment rankings revealing account names, dates and performance of users, also around military bases. This information is sensitive in a way that everyone knows who is stationed where and how fit they are.

Veenstra clarifies however, that data for training purposes is less sensitive to be picked up while transferring and even wireless communication could be used (personal communication, October 10, 2019).

While wireless data transfer might be considered safe, official 'sharing' of data to different user(account)s is bound to General Data Protection Regulation (GDPR or in Dutch: AVG). A user always need to give consent to share any personal data with other people, including medical staff (M. de Jong, Personal communication, January 15th, 2020). It is even forbidden for most occupations to ask an employee to start using and sharing any kind of personal data. The exception, however, is made for Defence personnel for the purpose of employability information.

When it comes to medical data, there are more strict rules about its privacy. Officially, data is considered 'medical' when it is obtained by a BIG-registered medical expert. Data obtained by a patient (or general user) itself is therefore not considered 'medical' and can be treated in a less confidential manner, according to M. de Jong. Medical data can always be shared between doctors and therapists treating the same patient.

5. POSSIBLE OUTCOME SCENARIOS

5.1 Choice of shoe wear

Detecting injury is just the first step towards the solution to actually prevent them from happening. With the results of an RT- PSM device, appropriate steps need to be taken to intervene on the problematic factor. Footwear of military recruits is build to be resistant to impactful contextual factors such as rocks, rain, mud and sand. They are build to be strong and durable, which isn't the best combination with a factor of comfort for the user. Recruits of the Royal Netherlands Armed Forces wear Haix combat boots (see Figure 7). Even though the brand claims that these boots are lightweight and ergonomically designed (Legerlaarzen van Haix, n.d.), the high sole stiffness has an effect on joint load. The damping factor of footwear shows a two-sided argument. On the one side, cushioning could induce shock absorption, on the other hand, it could limit proprioception of the foot.

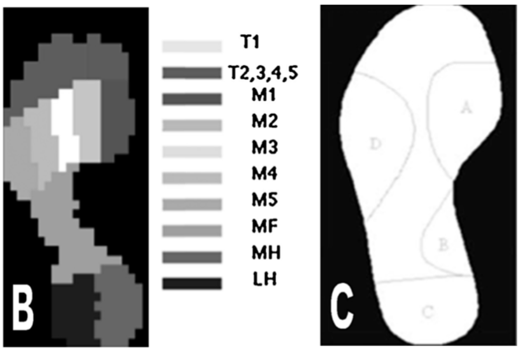
Figure A3.7 - Standard military boot (HAIX, n.d.)

5.2 Customized insole orthosis

The shoe insole is the interface between the foot and footwear (Nagano, 2018). Its geometry and fitting determines the load distribution and damping of the user's biomechanical behavior during walking. A customized insole orthosis could change the ankle angle, increase contact area, adjust resilience, create better contact surface and provide assistive support. Other types of insoles - such as a lateral wedge insole (Figure 8) - could assist in effective medial-lateral movements to reduce forces moving up the lower limb bones and joints (e.g. knee adduction moment).

Figure A3.8 - Lateral wedge insole (Amazon, n.d.)

Franklyn-Miller et al (2014) argued possible corrections with orthoses based on plantar pressure loading formulas and their area (Figure 9).



Correction	Calculation
A+ Fore Foot correction (anti-pronation)	(M1+M2)/ (M1+M2+M3+M4+M5)
DF-, Anti inversion element, lateral stabiliser	(M3+M4+M5)/ (M1+M2+M3+M4+M5)
B+, Mid foot correction(Anti-pronation)	(M1+M2+HM)/ (M1+M2+M3+M4+M5+HM +HL)
C, Rearfoot Correction Anti-valgus	(HM)/(HM+HL)

Fig. 2. The areas of Correction and the ratio calculation formulae.

Figure A3.9 - (a) Areas of Interest under the foot, (b) Areas of correction under the foot (c) Ratio calculation for foot corrections (Franklyn-Miller et al, 2014)

Figure A3.10 - Insole milling machine (Voxelcare, n.d.)

Figure A3.11 - Customized 3D printed insole (GoFar, n.d.)

Customized insole orthoses can be fabricated both manually or by automated methods such as milling (Figure 10) or 3D printing (Figure 11). For most methods, a static 2D or 3D print of the foot sole is used, accompanied by a certain pain complaint and joint kinematics tests (Schrijver, personal communication, October 3, 2019). However, static pressure distribution is not representative for plantar pressure distribution during the entire gait (Ong & Wong, 2005). Therefore, some brands such as Superfeet (ME3D) additionally uses a dynamic pressure pattern using a force plate. However, specification of pain complaints are still necessary for deciding on the type and shape of orthose. The pain complaints are also needed for the customer to come by in the first place, as most people are not aware of their poor foot function without it causing pain.

When fabricating the insole orthosis, the type of shoe where the insole will be inserted in should be accounted for. If the inside of the shoe has a different shape than the insole orthosis, its functional customized shape will be deformed and lose its function.

5.2 Gait retraining

A combination of exercises to improve neuromuscular control has been shown to reduce biomechanical risk factors that lead to OLLIs (Sharma, 2014; Zimmerman et al, 2018). A study by Sharma (2014) put a group of 83 participant with increased risk for MTSS on a gait retraining program. This program included three sessions per week training flexibility (stretching) and neuromuscular control (exercises in a gym) and one session per week focusing on biofeedback (footfall, landing impact and foot eversion control in a laboratory setting). Figure A3.12 shows a significant reduction of injury of about 75% of the intervention group across the 26-week training program.

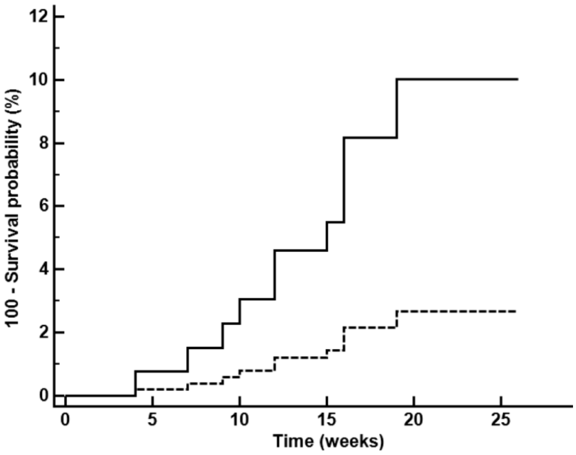


Figure A3.12 - Survival probability plot for Medial Tibial Stress Syndrome. (Solid line, control; dashed line, intervention) (Sharma, 2014)

Other gait retraining intervention methods could be related to stride length (Hoffman et al, 2015; Schrijvers, personal communication, October 3, 2019; Zimmerman, et al, 2018). The smaller the steps, the lower the impact force per step. In running biomechanics, braking impact and footfall pattern are seen as potential gait retraining methods. For walking biomechanics however, they might have a different effect. Specific training of lateral ligaments might also offer solution to prevent injury after forced inversion on uneven ground (Rice et al, 2013). Additional focus on posture during walking or running (not to bend over at the waist) is also used as a military gait retraining focus by Zimmerman et al (2018). Gait retraining is already provided as a treatment in military setting, but it is not yet used as a method of injury prevention as there is no method to detect recruits with increased risk. Also, according to van Valderen (personal communication, december 4, 2019), they have not been able to test the effects of gait retraining in outdoor situations. Gait retraining could be offered to a group of recruits that is selected according to the RT-PSM diagnostics and could be provided by a physiotherapist or sports instructor of a military unit (see paragraph 4.2).

6. MEASURING WALKING PARAMETERS

6.1 Risk factors

Intrinsic risk factors can be discovered in the field of anthropometric (body build), kinematic (human motion) and kinetic (acting of external forces on a body in motion) parameters.

Table 2 shows an overview of some studies that proved significant correlation between a biomechanical parameter and an injury type. Most relevant parameters per group (marked bold) are explained and elaborated in this paragraph.

Table 2 - Risk parameter and injury type overview

Parameter	Dependent factors	Injury type	Author(s)
Anthropometrics			
Static knee alignment / Tibial varus or valgus (TV)	KP / AA	Lower limb (unspecified), Stress fractures; Ankle sprains, ITBS	Cowan (1996); Milner et al (2006); Sharma (2007); Verrelst et al (2018); Strauss et al (2011)
Forefoot circumference (and swelling) (FFC)	PP	Local skin discomfort, Metatarsalgia	Schrijver (2019, personal communication)
Static Ankle Alignment (, subtalar and forefoot varus or valgus) (AA)	TV / KP	Stress fractures	Milner et al (2006); Matheson et al (1987)
Quadriceps angle (QA)	Stiff tendons	Stress fracture	Cowan (1996)
Foot arch height (hollow / flat foot) (FAH)	Short / stiff heel tendon / tibial varum / Calcaneal eversion	Plantar fasciitis, MTSS, heel spurs, Achilles tendinopathy	Carson et al (2012); Schrijver (2019, personal communication)
Short / stiff heel and calf tendons	Hollow foot; QA	Plantar fasciitis, Heel spurs, Achilles tendinopathy, Metatarsalgia	Schrijver (2019, personal communication)
Kinematics			
Peak tibial shock (PTS) / Positive tibial acceleration		Stress fractures, heel spurs, plantar fasciitis, MTSS, patellofemoral pain syndrome, pain in the hip, knee and lower back, ITBS	Milner et al (2006); Daoud (2012); Rice et al (2018); Strauss et al (2011)
Knee Pronation (KP) / Tibial Adduction	PP (big toe) ; B	Stress fractures, Patellar tendinopathy, Patellofemoral pain syndrome, ITBS	Milner et al (2006); Schrijver (2019, personal communication); Strauss et al (2011)

Tibial (knee) Free Moment (TFM)	PP ; AFM ; MP ; JPA	Achilles tendinopathy; Stress fractures	Azevedo et al (2009) ; Verrelst et al (2018) ; Milner et al (2006) ; Arendse et al (2004)
Ankle Free moment (AFM)	JPA ; MA	Plantar fasciitis, Hallux valgus	Arendse et al (2004)
Muscle pre-activation (MA)	JPA	Achilles tendinopathy	Azevedo et al (2009)
Strike footfall pattern - RF, FF, MF (FP)	SL ; VLR ; VIP ; TFM ; AFM		Arendse et al (2004)
Joint power absorption (JPA)	TFM ; AFM; WS; TFM; MA; PTS		Nagano et al (2018)
(Mid)foot pronation (MP)	PP ; TFM ; TFM ; VIP ; VLR; WS; iCoP	Medial Tibial Stress Syndrome, Heel spurs, Plantar fasciitis, Hallux valgus, ITBS	Bennet et al (2001) ; Nagano (2018) ; Willems et al (2007)
Time to reach peak heel rotation	MP; iCoP; JPA	Medial Tibial Stress Syndrome	Sharma et al (2011)
CoP at initial contact (iCoP)	MP	Lower limb (unspecified)	Willems et al (2007)
Calcaneal (rearfoot) eversion	KP ; PP ; FAH ; MP	Ankle sprains, Tibial Stress Fracture	Verrelst et al (2018) ; Pohl et al (2008)
Walking speed (WS)	C ; SL		
Cadence (C)	ES ; VIP ; SL	Stress fractures, MTSS	Milner et al (2006)
Stride length (SL)	WS ; C ; VIP	Stress fractures, MTSS	Milner et al (2006); van Tiggelen (2019, personal communication)
Balance (B) / Centre of Pressure trajectory	WS ; KP ; PP	Medial Tibial Stress Syndrome and Stress fractures	De la Cruz (2014); Willems et al (2006)
Kinetics			

Plantar pressure distribution (PP) / heel rotation (medial vs lateral heel pressure)	MP ; AFM ; KP ; B; FFC ; FP	Medial Tibial Stress Syndrome and Stress fractures	Willems et al (2006); Sharma (2013)
Asymmetry in kinetics		Lower limb (unspecified)	Mokha et al (2016)
Laterally directed force distribution in mid-stance		Achilles tendinopathy	Van Ginkel et al (2009)
Vertical impact peak (VIP)	C ; VIP ; VLR ; SL ; MP	Stress fractures, Metatarsalgia, MTSS; Patellofemoral Pain Syndrome (under metatarsal 2 and lateral heel)	Milner et al (2006); Nagano et al (2018); van Ginkel et al (2009); Zimmermann et al (2018)
Vertical loading rate (VLR)	VIP ; C ; SL ; MP	Stress fractures	Milner et al (2006) ; Nagano et al (2018) ; Willems et al (2007)
Extrinsic factors			
Fit of footwear	PP	Metatarsalgia; local pressure points; blisters	
Load carrying			
Terrain type (e.g. camber, hardness, smoothness)	JPA ; TFM	ITBS	Strauss et al (2011)

Anthropometrics

Before even looking at dynamic walking parameters, static anthropometric data already provides insight in potential risk factors. A common lower limb deformity, where the distal segment is bend either inward (valgus) or outward (varus) (see Figure 13), causes malalignment of the knees and creates abnormality in gait (Sharma, 2007).

When performing physical exercise (PE), varus knees will cause greater bending moments as the vertical loading is projecting medial to the tibial segment (Milner, 2006), increasing risk for Tibial stress fractures. Malalignment also causes increased stress on joint tissue, contributing to development of knee osteoarthritis (Sharma, 2007) or other injuries such as ITBS (Strauss et al, 2011).

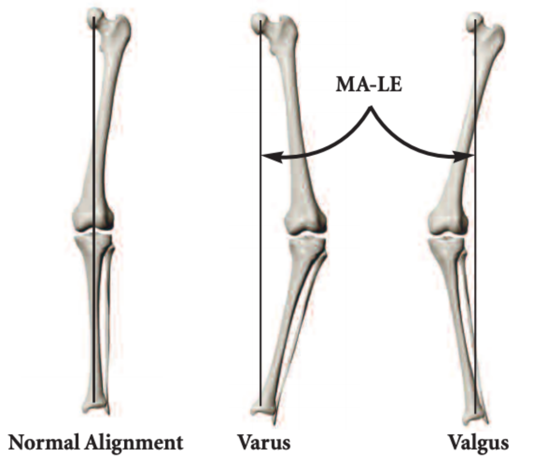


Figure A3.13 - Knee alignment types (Kenneth, 2008)

Malalignment can be measured with optoelectronic or inertial sensors. So far, this has only been done placing inertial sensors on at least the shank and thigh and often also on the pelvis (McGrath et al, 2018; Vitali et al, 2017). Noehren et al (2007) found a significant higher average knee internal rotation peak of 3.9° of runners developing ITBS compared to the control group.

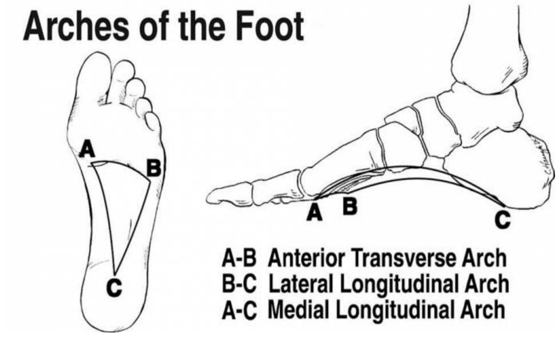


Figure A3.14 - Arches of the foot (Wilson, 2015)

Foot arch height (FAH) also has significant impact on injury risk. A study by Carson et al (2012) showed that people with high medial longitudinal arch (see Figure 14) are less able to absorb shock due to increased rigidity in foot mechanics. Large FAH causes peak forces in the medial forefoot and lateral rearfoot, increasing chance of injuries such as metatarsal and calcaneal stress fractures. High arch also comes paired with increased stiffness of plantaris ligaments in the of the foot and Achilles heel (Schrijver, personal communication, October 3, 2019), increasing stress during dorsiflexion of ankle and toes during the terminal stance phase. This increases risk of injuries such as heel spurs, plantar fasciitis and Achilles tendinopathy. Pes planus (flatfoot) foot structures are less associated with instances of OLLI. FAH can be measured either with pressure peaks under the medial forefoot and lateral rearfoot, but a more accurate calculation is the foot arch index (FAI), using a 2D footprint (Menz, 2012) (see Figure 15).

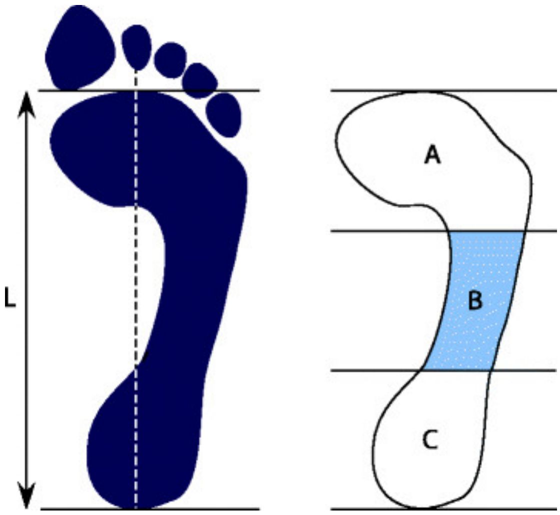


Figure A3.15 - Calculation of the FAI: Divide the length of the foot - excluding toes - in three parts. The middle area divided by the entire area gives the AI (AI = B/A + B + C) (Menz, 2012)

Kinematics

Kinematics describes human motion throughout the gait. A retrospective study from Pohl et al (2008), found an 83% accurate prediction for Tibial stress fractures combining data from lower limb joint range of motion and free moment. Reduced knee range of motion increases forefoot pressure during toe-off (Schrijver, personal communication, October 3, 2019; Mann, 2016). Increased bending moments of the tibia is also correlated to increased VLR and PTS (Milner et al, 2006).

Milner et al (2006) found a 70% accuracy of tibial stress fracture prediction with people with higher PTS (or positive peak acceleration) during stance. PTS should be measured using a triaxial accelerometer on the distal tibia, measuring in axial, anterior-posterior and medial-lateral directions (Rice et al, 2018). Acceleration values can be measured in m.s/s or g (where 1 g = 9.81 m.s/2). Threshold of 5g, 10g and 15g can be considered the boundaries of moderate, high and very high peak tibial shock. And the number of peaks per minute could indicate for overuse actions. However, since VLR and PTS are found to be significantly correlated in multiple studies, measuring only one of them could be sufficient to provide a diagnosis of OLLI risk. Alternatively, Grau et al (2011) found a higher incidence of ITBS with participants with lower maximum knee flexion velocity.

Abnormal direction of motion, such as knee and midfoot pronation and calcaneal (RF) eversion, have been connected to injury incidence multiple studies (Milner et al, 2006; Schrijver, personal communication, October 3, 2019; Bennet et al, 2001; Nagano, 2018; Pohl, 2008). Willems (2007) found a significant higher tri-planal pronation excursion (°) in pre-injured participants (54.2 ± 10.1) compared to non-injured participants (50.3 ± 8.1), where the CoP at initial contact of the pre-injured group was located significantly more lateral (25.58 mm ± 11.36) than the uninjured group (20.96 mm ± 9.35). Koh et al (2015) found a higher pressure (KPa) in medial forefoot in pronated feet (104.5 ± 51.0) vs normal feet (60.9 ± 25.1) during static squat exercise, which indicates that foot pronation can also be measured using pressure data.

While the rate of above-mentioned variables serve as an injury indicator, also the timing of the parameter's execution tells something about its risk factor. This aspect of timing in a large scale relates to walking speed and cadence and their influence on stride length. A larger stride length with similar walking speed compared to someone with smaller stride length, will show increased VLR and PTS (Schrijver, personal communication, October 3, 2019). On a smaller scale, stance pattern timing also influences loading. For example, a delayed maximal eversion of the foot (caused by a lateral footfall) is found in participants that developed OLLI's (Willems, 2005-2007), where uninjured participants averaged out on 47.2 ± 12.1 and injured participants on 51.8 ± 10.0 (% of stance phase). The same study found a significant higher mean re-inversion velocity (°/s) of pre-injured participants (96.7 ± 136) compared to non-injured participants (81.6 ± 50.4). A study by Sharma et al (2011) found a mean of 22,5% of stance as normal time to reach peak heel rotation (=HL-HR), where only 1 SD (3.0%) away from that mean is concerned a risk factor and 2 SD predicts high risk.

Kinetics

Kinetics describe the force and pressure parameters acting on the human body while moving. They are often influenced by anthropometrics and kinematics but include external forces (such as ground reaction force). During gait, the body balances itself applying weight distribution over one or two legs. This balance creates a continuous change of Centre of Pressure (CoP) under the foot (Booth et al, 2019). When increasing the walking speed, the CoP diverges more to the medial side of the foot. Sharma et al (2014) proposed an algorithm of the medial-lateral pressure differential to calculate foot balance, from 9 distinct areas (Medial Heel, Lateral Heel, Metatarsal Heads M1,M2,M3,M4,M5 and the Hallux, T1). Calculating 'foot balance' value using (=M1+M2+HM-M3-M4-M5-HL) in the first 10% of the stance, will provide a risk assessment for MTSS. With a value of -14 $N.cm^{-2}$, the intervention group showed increased foot balance. Only 1 SD (4.2 $N.cm^{-2}$) already predicts risk of injury and 2 SD predicts high risk. This kind of data can be used to identify risk factors for inversion sprains and OLLI's (Willems et al, 2005). An example of a visual CoP trajectory can be found in Figure 16.

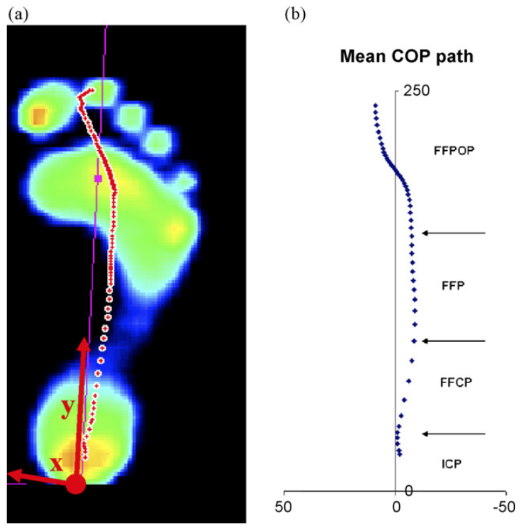


Figure A3.16 - Centre of Pressure trajectory (de cock et al, 2008)

Vertical loading rate (VLR), Vertical impact peak (VIP) and local Plantar pressure (PP) are all measured with plantar pressure analysis (Mann, 2016; Booth et al, 2018; Daoud et al, 2012). Plantar pressure measurement is proven to be reliable in test–retest (Franklyn-Miller et al., 2014). Figure A3.17 shows a graph of peak plantar pressure depending on walking speed in different areas under the foot. Visible is that the peak pressure under the central forefoot reaches the highest values. 1000 KPa could be seen as a threshold towards medical implications (Guldemond, 2007). The toes play an important role in reducing local plantar pressure peaks by increasing load-bearing area (Guldemond, 2007).

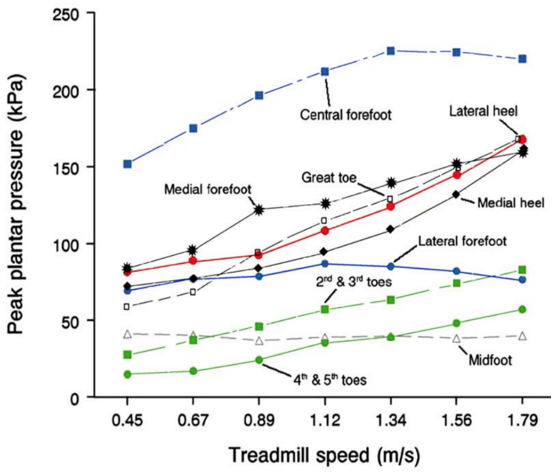


Figure A3.17 - Plantar pressure as a function of walking speed (Guldemond, 2007; Warren et al., 2003)

Vertical impact peak is the highest value of sample-to-sample vGRF loading. It occurs during heel strike, which magnitude is affected by i.a. walking speed, footwear and footfall pattern (Daoud et al, 2012). VIP is hypothesized to cause injuries such as stress fractures, plantar fasciitis, MTSS, patellofemoral pain syndrome and pain in the hip, knee and lower back (Milner et al, 2006; Daoud et al, 2012). This is related to the impact of the shock traveling up the body generating stress and strain in skeletal tissue, which in its turn generates high levels of elastic hysteresis. Small doses of these shocks are often harmless, but as mentioned before, repetition of impact creates accumulation of micro trauma to build up to an injury.

Vertical loading rate is measured using force sensors under the foot and calculating difference in vGRF over a period of time (20%-80% until impact peak, see Figure 4). Milner et al (2006) found a mean VLR of 79.65 (18.81) BW.s^{-1} in a control group and a significantly increased VLR of 92.56 (24.74) BW.s^{-1} for people with a history of Tibial stress fracture. Willems (2007) on the other hand, found significant lower VLR values of pre-injured participants under metatarsal 5 (1.70 ± 0.63) (N.s.cm^{-2}) and lateral heel (0.65 ± 0.17) compared to uninjured participants (2.01 ± 1.08 and 0.74 ± 0.40). He also found a higher peak pressure underneath the medial side of the foot (M1) at forefoot flat and at heel-off.

Even though many studies are able to provide significant predictive values for intrinsic factors, many suggest that the factor of repetitions of smaller loading rates will result in higher risk of injury. However, there are fewer studies found to compare those.

6.2 Measurement types

Measurement of biomechanical loading depends on the parameters required for injury prediction and is typically done in three different forms: force/pressure sensing, contact area sensing or movement sensing. Table 3 shows an overview of measurement types available to measure the parameters as discussed in section 6.1.

Table 3 - Measurement type overview

Measurement tool	Measuring parameter(s)	Advantages	Disadvantages	Example product
Force and pressure sensing				
(All)	CoP trajectory; ViP; Foot arch height;; Midfoot pronation			

	height;; Midfoot pronation (mm); Strike Index (% of sole length); Single / double support duration; Cadence			
Pressure plate [3]	Plantar peak pressure; Contact area; Centre of mass (CoM) ; Base of Support (BoS);	Can provide detailed information about weight distribution and ankle kinematics; High spatial resolution [9]	Only suitable for laboratory use; Unable to capture multiple, consecutive steps [3]; Provides complex data	F-scan pedar; Footscan; Pressure treadmill; Pressure carpet
Force plate	Force distribution area	High resolution detailed data ; Reliable in test and re-test [1]; High spatial resolution [9]	Only suitable for laboratory use; Unable to capture multiple, consecutive steps [3]; Provides complex data	AMTI optima force plate; Footscan by RSScan ; Novel emed-x
Glass top force plate	Force distribution area; non-contact foot parameters	High resolution detailed data ; Reliable in test and re-test [1]; No ground contact needed; High spatial resolution [9]	Only suitable for laboratory use; Unable to capture multiple, consecutive steps [3]; Provides complex data	
Load cell (hydraulic, pneumatic or strain gauges)		Very accurate [10]	Bulky in size [10], not flexible	Honeywell model 13
Force sensitive resistors (FSR) /		Thin, lightweight, flexible, customizable [10]; Stays	Vulnerable to damage caused by excessive or repetitive loading [9]; less accurate than	PI Bioelectronics sensor array

Piezoresistive force sensor		constant after multiple cycles	load cell [10]; Fabrication irregular	
Piezoelectric sensors / hydrocells [4]	Force, pressure, acceleration and temperature	Measures multiple variables; inherent reliability; no deformation	Vulnerable to damage caused by excessive or repetitive loading [9]; Sensitive to temperature changes	Maruta electronics BB-20-6L0
Contact area sensing				
Discrete array	Discrete contact area under the foot	Required technology is simple, inexpensive and easy to use for the evaluation of bare feet and shoes [9]	If used locally, placement is variable according to individual anatomy. Could be solved by integrating into an array.	
Spatial/ switch sensor	Discrete contact area under the foot	Simple technology	Only provides the contact area, but not the quantity of pressure.	
Movement sensing				
(All)	Asymmetry in kinetics; Peak tibial shock; Cadence; Step length			
Gyroscope	Knee width ratio (valgus knees); Quadriceps angle; Calcaneal eversion; Tibial varum; Strike Index (% of sole length);	Simple in combine with wavelet transform ; can be placed anywhere on the segment ; Can be used for long time trials ; light ; low cost [6]	Gait events (e.g. heel strike and toe-off) are transitory signals that cannot be properly enhanced by traditional signal processing ; sensitive to temperature and shock ; shows drift and artefact [6]; Needs to be calibrated and	ADIS16350

			distorts on uneven terrain	
Accelerometer	Midfoot pronation (mm); Free Moment (FM) of the Tibia and foot (Nm);	Small sensor ; Accurate data	Signal is often biased by the grav. acc. and depends on the attachment site along the segment (e.g. limb) ; needs specific placement can provide noisy output [6]	ADAfruit 2809 (3 or 9 axis)
Inertial Measurement Unit (IMU)	Midfoot pronation (mm); Free Moment (FM) of the Tibia and foot (Nm); Strike Index (% of sole length); Joint ROM (pelvis, knee, ankle);	Multiple sensors in one unit; same as gyroscope and accelerometer	Same as gyroscope and accelerometer	InvenSense, MPU-9250
Optoelectronic motion sensing	Joint ROM (pelvis, knee, ankle)		Only suitable for laboratory use;	VICON ; Optotrak Certus
Electromyography	Muscle activation (Hz)	Measures internal loads	Needs to be adhesed to the skin	Telemetric EMG

References:
[1] Franklyn-Miller et al (2014)
[2] Mokha et al (2016)
[3] Mann (2015)
[4] Benocci et al (2009)
[5] Lawrence & Schmidt (1997)
[6] Aminian (2006)
[7] Shahabpoor et al (2018)
[8] Clark et al (2017)
[9] Guldemond (2007)
[10] Load Cell Vs. Force Sensor (n.d.)

Force / pressure plates

Plantar pressure under de foot gives a good indication of stress as it accounts for force and contact area. Force and pressure plates provide detailed and high spatiotemporal resolution data which makes outcome very accurate. Glass-top force plates additionally measure non-contact parameters. However, force or sensor plates are only suitable for laboratory use.

Force / pressure sensors

If a measurement application is integrated inside a wearable device, sensor requirements should be considered according to its use. The first consideration to make is the spatiotemporal resolution of the sensor design. Sensor placement should be done according to the specified sensing requirements. Section 6.1 showed the potential for measuring under the lateral, medial and central forefoot, along with medial and lateral heel and the Hallux, but also for measuring the contact area under the foot. Higher spatial resolution makes the estimates more accurate, but with appropriate algorithms it is possible to calculate pressure values under the entire foot, without the need to cover the entire insole with sensors. Additionally, some sensor locations are highly correlated (Figure 18) and could be considered to be merged (Benocci et al, 2009). Lawrence & Schmidt (1997) found a combination of only four sensor locations to calculate approximate weight on each foot and the CoP trajectory.

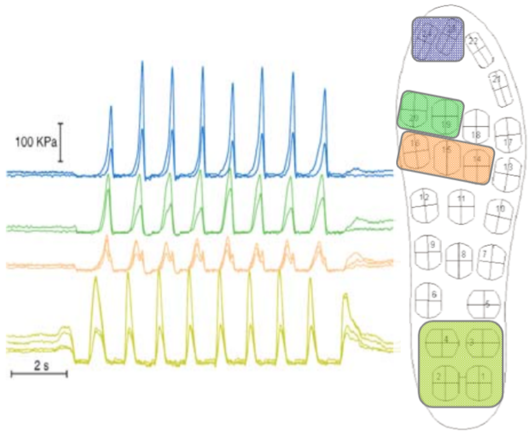


Figure A3.18 - Groups of highly inter-correlated sensors during gait measurement (Benocci et al, 2009)

For measuring gait activities, a sampling frequency of 200 Hz would suffice (Razak et al, 2012). Lowering this frequency could cause the system to miss the actual peak values.

The dynamic range of peak pressure values in normal subjects is very large, not to consider influence of shoe wear and terrain type. Dynamic range also differs between areas under the foot (Figure 19). For many clinical conditions plantar pressures not higher than 1000 kPa already require medical consultancy, for which a dynamic range with 1270 kPa would suffice. For heavy-packed military soldiers (e.g. 150 Kg) and sports applications (e.g. running = BW x 2.5), the maximum values could rise up to about 3 MPa (Razak et al, 2012). With these high values, the burst pressure should be at least 3 MPa, which is typically used in these kinds of applications. Pressure sensors can also be used to solely detect the contact area, for which detection of up to 50 or 100 kPa would suffice. Whether or not the absolute plantar pressure value is important for calculating risk factors should be considered to choose dynamic range of the pressure sensors.

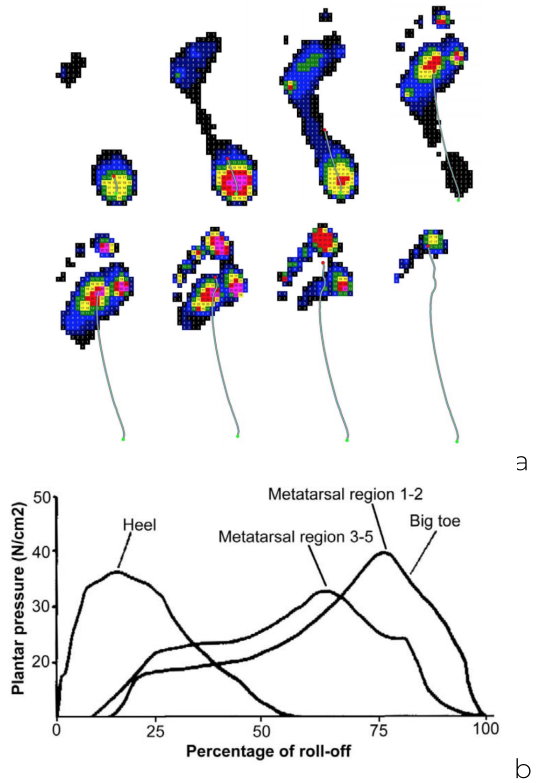


Figure A3.19 - (a) Plantar pressure contact area throughout stance, (b) Local peak pressure during walking (Guldemond, 2007)

Low power consumption should be strived for when selecting the right sensors. This requirement is inversely proportional to requirements such as high spatiotemporal resolution and dynamic range, which means the right balance should be found.

Movement sensing (IMU)

Kinematic data can be measured using another type of sensor. An inertial measurement unit (IMU) is a sensor package including an accelerometer, a gyroscope and a magnetometer and is therefore able to measure accurate kinematics in 3D space. Applications could be to measure joint kinematics, but also the more detailed pronation and supination of the heel and metatarsal area.

Even kinetic data such as ground reaction force can be calculated with an IMU, using the acceleration and data from total body weight (and packaging) (Shahabpoor et al 2018). With the formula GRF_v (t) = m_{total} x (g + x_v(t)), where x_v represents the vertical movement of the body CoM. Study done by Shabpoor et al found the optimal location for the IMU - to calculate GRF - to be on the neck (C7) or head.

The downsides to IMU applications are the requirement of specific placement - especially when knee kinematics are measured - the need for gyroscope calibration and distortion in uneven terrain, sensitivity to temperature, shock, tissue artefact and initial gravitational acceleration which will provide noisy output (Aminian, 2006). Using a low-pass filter, data from a skin-attached marker and thigh attachment could remove artefact issues and accurately represent bone movements (Sheerin et al, 2019).

Movement sensing (others)

Movement sensing can also be done with optoelectronic markers. Such system (e.g. VICON) uses multiple cameras in a laboratory setting to track markers placed on a moving body. There is no need to say that this solution is not suitable for this project, as measurements are taken outside of the lab.

Electromyography is a method of measuring muscle activation. Electrodes that are stuck on the skin measure the electrical activity produced by the underlying muscle. This technique allows for analysis of muscle load. Also this technique is not suitable for military application, as the electrodes need specific placement on the skin and can not be integrated into a single wearable.

6.3 Data processing and delivering

A self-controlled measurement device for military use should not be too complex. Presentation of data should be relevant, clear and within a certain quantity to be considered useful. The ideal balance should be found between (a) targeted data collecting for useful and efficient user interaction (b) the input width and depth necessary to explore the unknown.

To accomplish requirement a, a Minimum Viable Product (MVP) will be defined with requirements from the study in section 6.1 (Risk factors). The system input can be expanded with personal user data such as gender, body weight, shoe size, age and the distinguishment between left and right foot measurements, as all of these factors could influence the study outcome (Zhang et al, 2014 ; Cock et al, 2005 ; Beynnon et al, 2001, Keijsers et al, 2014 & Hagglund, 2009; Deberardinis, 2018).

Requirement b will be obtained by data reduction methods (Booth et al, 2019). Examples of PP data reductions are Regions of Interest (ROI), Region-Time Curves (ROI-TIME), Centre of Pressure Trajectories (COP, VOP) and Pressure Pattern Images (IMAGE). Many methods are based on clustering of values, makes a study simpler and, in a clearly hypothesised study, it can be justified. It should however be kept in mind that subsampling of data could lead to loss of valuable information (Booth et al, 2018). A well hypothesized research or design goal could justify this loss.

6.4 Conclusion

This chapter outlines the potential of measuring in-shoe walking parameters used to establish interventions for potential injury risk. Several investigators have already explored the in-situ possibilities for military injury reduction by intervention methods, but not all of them succeeded. Sharma (2015) argues the cause of these failures to lie in the nature of the interventions, designed to target all injuries instead of focusing on a specific injury. On the other hand, investigations focusing on a single, most relevant injury have reported positive findings (Sharma et al, 2014).

Taking this information in mind while looking at the available commercial products on the market (Appendix 4), a complete mismatch is visible. The clusters of market products are primarily focusing on multi-diagnostic, design-for-all equipment. While the research attributes for professional industry have been around for a while, consumer products are emerging only in the last few years, offering increased usability of the technology. Both markets - while often targeting a specific sport - focus on detection of all injuries measuring a wide range of parameters.

The study by Sharma also contradicts with the literature summarized in Table 3, showing that a small group of sensors are able to cover a wide range of biomechanical gait parameters. Also should be taken into account that there is still a large grey area of unknown risk factors. Without exploratory measurements, these unknowns will never be found.

A solution might lie in isolating *specific injuries* as parameters instead of *biomechanical parameters*. While detecting multiple injury types using a single device and using different problem solving techniques per case (as described in chapter 5), the best solution space could be enclosed. Another solution for converging focus of a product lies in data reduction for targeted user interaction.

CONCLUSIONS

As stated in the introduction, the study of intrinsic factors of the human gait brings great potential for injury prevention, especially with a user group that is exposed to intensive training sessions such as the military (Franklyn-Miller et al, 2014). This chapter presents the key-takeaways to be used in the next step of the project.

1. More (in-situ) research is needed to convincingly predict OLLI

Although many researches attempted to find strong predictors for Overuse Lower Limb Injury, the literature comes short in convincing correlations between walking parameters and injury risk. Some studies did find significant results and argue the importance to explore the causal effects of that parameter further. Many others argue the necessity to explore the entire scope of walking parameters for injury prediction as there just hasn't been done enough research, especially those performed in the field (in-situ). The quantitative effect of repetition is a major parameter that should be studied.

2. Demand for a (new) wearable RT-PSM device in the Dutch Defence

Laboratory (plantar) pressure plate testing is currently considered the golden standard for performing clinical gait analysis. However, the immobility of the research setup, the consequences of "platform targeting" (Mann, 2016), the restriction to a single footfall and barefoot running (Rothchild, 2015), effects of involuntary kinematic changes during training (Verrelst, 2018) and fatigue (Grech et al, 2016) make many researchers to conclude that there should be searched for an alternative - wearable - measurement solution.

Besides that, L. Linssen (research scientists at TNO and rehabilitation scientist), D. van Tiggelen (head physiotherapist of the Militair Ziekenhuis Koningin Astrid in Neder-Over-Heembeek) and J. Schrijvers (orthopaedic shoe consultant) (personal communication, September 2019) acknowledge the potential usefulness of mass-data availability of entire battalion throughout a specific training program for use of injury prevention, or to track the effects of gait retraining methods. It could decrease the rate of discharge caused by OLLI (10-26%) and reduce the rehabilitation time (13-21 weeks) (van Rompay, 2011). In general, prevention of injuries retains i.a. morbidity, training time, resources and manning of the entire army, which will be able to cut costs in the long term (Sharma, 2015). If the military would invest in RT-PSM devices to reduce injuries and which investment costs would stay below 60% of the estimate of €2300 (€1380) per recruit, in theory this will eventually save money.

That said, such a suggested wearable measuring tool, should be a usable tool for the end-user in terms of performance (see keypoint 3) and embodiment. The latter mainly comes down to integration within standard military boots, resistance to heavy loads, heat and humidity and the user interaction scenarios. Interaction scenarios will be elaborated later in the project. Even though the market already offers several pressure-measuring insole devices, none of them are suitable for military use.

3. Focus on three specific - most relevant - injury types

The data that is measured by existing wearable pressure insoles (e.g. Paromed, RSscan) is too complex, which makes them unsuitable for military purposes (Linssen, 2019; van Tiggelen, 2019; Aminian et al, 2005). Besides that, studies by Sharma et al (2014; 2015) have shown that focusing on a single injury instead of targeting all possible injuries will improve the quality of the diagnostics. Using combined risk factor models, the predictive power will increase (Sharma, 2013).

Looking at military recruits as the end-user, the focus of this study will lie on the prevention of injuries with both highest incidence and highest impact in terms of morbidity (see Figure 30). An overview of these injuries and the parametric risk factors that have been proven to evoke those injuries can be found in Table 2. Considering all studies in this literature review, focusing on three most common injuries: Medial Tibial Stress Syndrome (MTSS), Tibial Stress Fracture (TSF) and Iliotibial Band Syndrome (ITBS) - together covering at least 13,25% incidence of all recruits (van Rompay, 2011) and high morbidity impact - would have a significant positive impact on total drop-out rate. It should be noted that the estimate of 13,25% only includes the diagnosed cases. Assumed is that the actual impact number will be higher as many recruits with pain symptoms never see a doctor and don't get processed.

According to paragraph 6.1, the three injury types in theory could be measured with twelve different parameters (see Table 4). Some parameters measure multiple injury types. Some parameters are affected by other parameters (dependent parameters), which means that exclusion of one of them might be possible to predict an injury. Lastly, the table shows which type of measurement tool is able to measure the different parameters and which threshold could be assumed as high risk. These measurement tools are narrowed down to pressure sensing and IMU sensing according to results of paragraph 6.2 The values presented in Table 4 are found in literature, but often differ strongly per person and are sensitive to context and calibration method (Deberardinis, 2018). This means that it is possible to design an RT-PSM device to measure relevant walking parameters, but it is hard to give accurate advice on when a product will specify the threshold value within a few months to years increasing its accuracy over time, providing valuable data for multiple user groups. Also the input of personal data and characteristics will help to improve the accuracy of injury prediction. An example of such an input is

Figure A3.20 - Injury type focus (ITB, MTSS and TSF) smoking (Sharma, 2013). parameter threshold is exceeded by a user. However, with use of machine learning, the

4. Timing and repetition are important

Measuring quantitative values of the selected parameters will be accompanied by time-mapping to establish a dynamic analysis of the movement. Some parameters - such as time to peak heel rotation - are linked to timing within stance (Sharma, 2013; Nagano et al, 2018; De la cruz, 2014; Willems, 2007). Therefore, the system should be able to calculate gait cycle parameters including heel strike, foot-flat and toe off (together forming the stance phase). Measuring contralateral toe off, heel rise and contralateral heel strike also provides insight in the weight balance between two limbs.

Table 4 - Project focus: Risk parameters and how to measure them

Parameter		FAI %	**PTS** *g* ; m.s/2	**MP** °	iCoP *mm*	**C** s/m	**VIP** *BW*; KPa ; N.cm-2	VLR BW.s-1	**FB** *KPa* ; N.cm-2	TPHR %	**KP** ° ; mm	**CE** ° ; kPa	**TFM** *Nm*
Dependent parameter		SA / TA	SL	TFM / FB		VIP	SL	VIP / C / MP	MP / KP / FP	MP / iCoP	SA / FAH TA / iCoP	FAH / TA / SA	FB / MP
Injury type	MTSS												
	TSF												
	ITBS												
Risk-threshold value		<21 / >28 - high <15 / >34 - very high	5 - mod 10 - high 15 - Very high	50 - mod 54 - high	20 - mod 25 - high	<170 - mod <160 - high <150 - very high	1.70 - mod 1.80 - high 1.85 - very high	80 - mod 90 - high 95 - very high	-14 - mod -18 - high -22 - very high	25,5 - mod 28,5 - high	3.9	9.7	5,9 - mod 7.6 - high 9,3 - very high (x10-3)
Measurement	Pressure sensing												
	IMU sensing												

Table 4: parameters (Foot Arch Index = FAI; Peak Tibial Shock = PTS; Midfoot Pronation = MP; initial Centre of Pressure = iCoP; Cadence = C; Vertical Impact Peak = VIP; Vertical Loading Rate = VLR; Foot Balance = FB; Time to Peak Heel rotation = TPHR; Knee pronation = KP; Calcaneal eversion = CE; Tibial Free Moment = TFM) and injury types (Medial Tibial Band Syndrome = MTSS; Tibial Stress Fracture = TSF; Iliotibial Band syndrome = ITBS)

Besides that, it is important to note that the repetition of the movement is equally (if not more) important to estimate risk for injury as overuse injury is caused by an accumulation of micro-traumas (Hauret, 2010; Franklyn-Miller et al, 2014). Many studies found a correlation between numeric values of biomechanical parameters and injury prevalence, but not many studied the connection between repetition of biomechanical parameters and injury risk. The factor of repetitions should be analysed during use with machine learning.

5. Efficient use of data

The biomechanical data gathered with the insole can be used for different steps of action. Paragraph 5.2 describes the possibilities and importance of customized insole orthoses to battle OLLI complaints. The correction shape of an insole orthosis highly depends on the gait biomechanics, which should be - but often aren't - obtained dynamically to provide full-gait support. For most insole brands, a customer with pain complaints comes by in a store for a scan. However, using diagnostic measurements by an RT-PSM device, a manufacturer can customize the insole from a distance and send it to the customer by post. This way, the injury is diagnosed ánd treated before the pain complaints even have occurred.

An alternative - or supplementary - form of action is offering a gait retraining program for recruits with abnormal walking kinematics. Offering a few sessions per week focusing on neuromuscular control, flexibility and biofeedback, the risk for injury can be reduced with 60% (Sharma, 2014).

Lastly, as stated before, the data should be used for research purposes to refine risk factors and their threshold values. Data gathered in military setting can later be used for other sports or medical purposes such as rehabilitation monitoring after surgery, defining proper fit of external prosthesis and orthosis, fall-risk assessment of elderly or finding appropriate assistive devices (Aminian, 2002).

8. LIMITATIONS

This literature review shows that many researchers have attempted to study walking biomechanics with the focus on identifying potential risk factors. However, many studies argue the validity of the results due to apparatus or method limitations. These limitations might harm the validity of the conclusions drawn from literature review as well. Therefore, it is important to acknowledge these limitations and test important takeaways myself to confirm their validity.

As mentioned in the Conclusion (chapter 7), majority of the studies are performed in-labo, which could bring unwanted consequences to the data output.

Some studies focus on running related injuries as opposed to walking related injuries. The two have a lot in common but are still very different.

A number of studies used retrospective analysis to compare walking parameters to historical cases of injuries (Pohl et al, 2008). This approach is convenient in a sense of time consumption, because the research doesn't need wait for injury to occur. However, this approach does not take into account the possibility for a participant to have changed their walking behavior after the injury occurred.

Spatiotemporal subsampling of data has also been proven to harm the validity of gait analysis studies (Booth et al, 2018). Clustering of plantar pressure values makes a study simpler (Guldemond, 2007) and, in certain hypothesis-driven studies, it can be justified. Using data from a sensor array, an algorithm can very accurately calculate the CoP. Temporal data aggregation is a different story. Pressure constantly changes throughout the gait. One main recommendation of Booth et al. (2018) is to look at data in different stages of the gait cycle separately instead of averaging parameters out over the entire stance. This increases the extraction of significant values.

Few studies justify the clustering of individual foot measurements, when factors such as gender, body weight, shoe size, age and foot (left or right), could influence the outcome of the study (Milner, 2006; Zhang et al, 2014 ; Cock et al, 2005 ; Beynnon et al, 2001, Keijsers et al, 2014 & Hagglund, 2009, Deberardinis, 2018).

In paragraph 3.3, it was established that besides the biomechanical factors there are a number of extrinsic factors that shouldn't be ignored. Factors such as inadequate warm-up, loading (e.g. rucksack) poor (or worn-out) footwear, too tight shoes, accumulation of heat and humidity in the shoe, training intensity and terrain type can highly influence the incidence of injuries (Lacirignola, 2017; Preventing Injuries in Military Training, n.d.). Specific effects of these factors will not be examined within the scope of this graduation project but should be picked up further along the road.

Appendix 4.

MARKET STUDY

The market for insole measurement devices is still relatively young and mainly focusing on research purposes. The embodiment of many of the available insole measurement systems is robust and require external electronic pouches to be worn around the lower leg, which makes them inappropriate for commercial purposes or long-term use. The market for general RT-PSM however, exists a little longer. This chapter gives a brief overview of some of the most mentioned products and systems mentioned in literature and media.

JOHAN GPS sports technology

JOHAN sports is a Dutch company offering an accurate GPS tracking system to team sports such as soccer and field hockey (JOHAN-sports, n.d.). The device is worn on the back using a wearable garment and tracks a player's accelerations, (sprint) distance and power to track fitness and prevent injury.

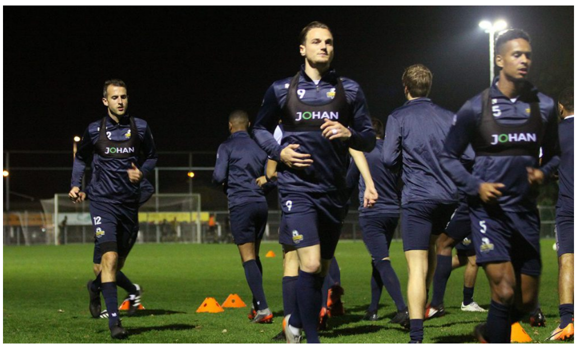


Figure A4.1 - JOHAN - GPS sports technology (JOHAN, n.d.)

Digitsole Podosmart

Digitsole is launching a multifunctional shock absorbing, foot support and measurement insole for activity tracking. The Digitsole is able to measure contact zone, balance, pronation/supination, flight/contact ratio, stride length and stability, cushioning, speed and propulsion. The insole has an integrated microprocessor in the heel and a usb port to charge. The design is easy to clean with water and soap. Connection to the app goes via Bluetooth, where data from one or multiple pairs of insoles can be collected and analysed with the Podosmart software. A pair of Digitsole insoles costs €129,90 and will be launched in October 2019.

Figure A4.2 - Digitsole by Podosmart (Digitsole.com, n.d.)

RUNVI RUNVI

RUNVI, is a kickstarter project that intends to use 30 pressure sensors and two accelerometers for real-time run feedback. The electronics are integrated in the insole heel, giving the insole a predefined shape (Figure A4.3).

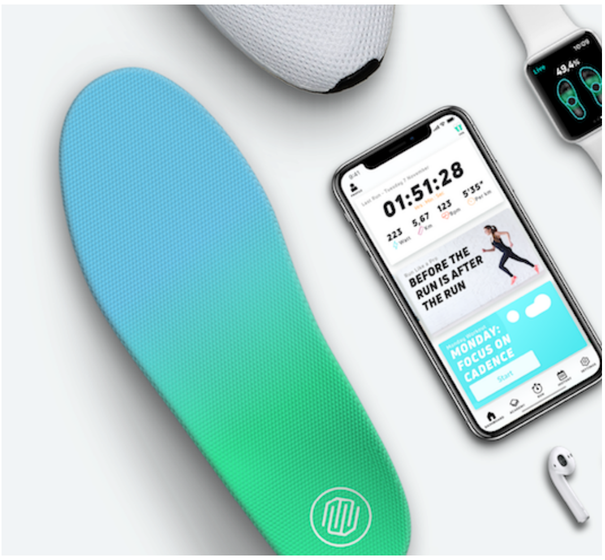


Figure A4.3 - RUNVI insoles (von Waldthousen, 2018)

FeetMe FeetMe

FeetMe is designed for rehabilitation of patients with a mobility disorder in hospitals. Similar to RUNVI, it uses pressure sensors and inertial sensors (Feetme, n.d.). Both these products have not been officially released on the market (Figure A4.4).

Figure A4.4 - FeetMe insoles ("Feetme insole", n.d.)

Novel Emed | Pedar | loadsol

Munich-based Novel is one of the leading companies in pressure and force sensing systems for the research industry. They provide both products and services to researchers applied to their needs. For the application of lower limb gait sensing, they offer three products (Products, n.d.). The Emed® (Pressure plate) en Pedar® (in-shoe sensing) are gold standard in measuring pressure distribution and local loads under the foot. The Loadsol® measures total plantar normal force inside the shoe. Their products come with extended software for data analysis. Besides their standard products, they provide custom sensor development for research.

Figure A4.5 - Pedar-r (Novel, n.d.)

Paromed Paroscan | ParoTec

Paromed has multiple footscanners in different sizes and functions. An example is their mobile Paroscan 3DIpad for mobile use (see Figure 23). This product is able to scan a foot or foam impressions and translate the data into the accompanying paroManager app or paroContour software which helps the user to make customized (milled) insoles for every foot type.


Figure A4.6 - Paroscan (Paromed DE, n.d.)

The Australian branch of Paromed created an in-shoe measurement device called ParoTec based on hydrocell technology (ParoTec, n.d.). The hydrocells inside the insole employ piezoresistive sensors which both statically and dynamically measure pressure distribution. The data is stored in a card in the controller. The same paroManager software can be used for customized insole fabrication and gait measuring.

Figure A4.7 - ParoTec (Paromed AU, n.d.)

GaitUp Physilog

The GaitUp is a simple versatile Inertial Measurement Unit with barometer used for gait analysis, activity monitoring sports and veterinary movements (Physilog, n.d.). This product proves that using just a simple, novel sensor device, enough measurements can be performed to make an accurate gait analysis.

Figure A4.8 - Physilog (GaitUp, n.d.)

RSscan footscan

RSscan is one of the leaders in foot measuring hardware. The Paal (Belgium) based company focuses on preventing injuries by measuring pressure distribution. Their primary product is the footscan®-system, which was initiated by the CEO of Adidas, with the goal to innovate in sports shoes to prevent injuries (Geschiedenis, n.d.). RSscan provides products for i.a. research labs, shoe stores and medical clinics.

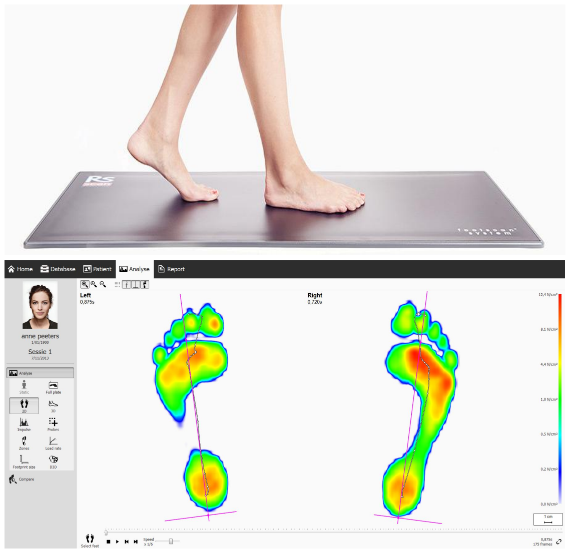


Figure A4.9 - Footscan (RSScan.com, n.d.)

AMTI optima force plate

AMTI offers a new technology for gait and biomechanical force measurements, where activities on the plate can be observed and recorder from underneath (Home, n.d.). Next to this new ASTM F3109-16 accuracy standard product, they offer other high-tech force plates and sensors.

Figure A4.10 - Optima force plate (AMTI Force and Motion, n.d.)

Figure A4.11 a and b show a two-axis overview of the products mentioned above. The products are rated along four categories:

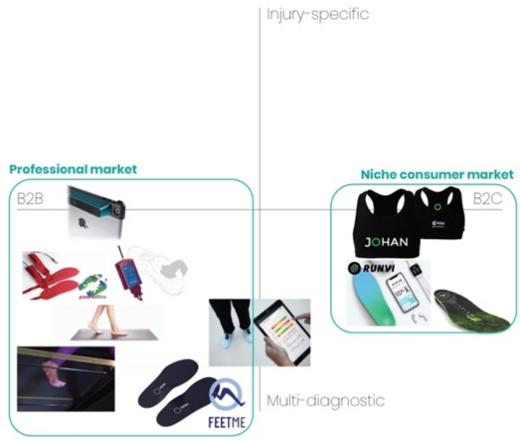
- Design purpose (accuracy vs usability)
- User specification (user-centered vs design for all)
- Business model (Business-to-Business vs Business-to-Consumer)
- Measurement capability (injury specific vs multi-diagnostic)

Figure A4.11 - Market segmentation maps (a) User centered design vs Design for all and Accurate vs usable, (b) Injury-specific vs Multi-diagnostic and B2B vs B2C

Within these visuals, four general clusters can be distinguished:

- Research attributes
- Generic tools
- Large professional market
- Niche consumer oriented

On the other hand, there are some market gaps where none of the products fit in.



These gaps combine ***accuracy with user-centered design*** and a ***multi-diagnostic product for both the business and consumer market***.

This market study provides valuable information that can be used to design not only a good product, but also a product with market viability.

Appendix 5.

STATISTICAL ANALYSIS STUDY 2 AND 3

Index

1. General

1.1 Descriptives general

Group		Cadence (s/min)	Step time (s)	Stride time (s)	Overall Peak Pressure (bar)	Vertical Impact Peak (bar)	Vertical Impact Peak (%)
Injured-Shoes	Mean	128.62	.46685	.96854	13.46006	3.65596	26.8570
	N	144	144	144	144	144	144
	Std. Deviation	9.402	.032182	.033640	1.862584	.536908	4.35371
	Std. Error of Mean	.784	.002682	.002803	.155215	.044742	.36281
Healthy-Shoes	Mean	112.85	.52324	1.02566	12.57215	3.07270	25.6628
	N	157	168	168	168	168	168
	Std. Deviation	6.564	.042253	.037573	2.168725	1.149622	3.69484
	Std. Error of Mean	.524	.003260	.002899	.167321	.088695	.28506
Healthy-Boots	Mean	129.67	.49919	1.05048	10.76208	2.64737	22.8897
	N	116	116	141	141	141	141
	Std. Deviation	66.886	.075867	.067255	3.453840	1.429307	11.71500
	Std. Error of Mean	6.210	.007044	.005664	.290866	.120369	.98658
Total	Mean	122.97	.49775	1.01523	12.29100	3.12572	25.1793
	N	417	428	453	453	453	453
	Std. Deviation	36.681	.056332	.058337	2.779233	1.172289	7.49452
	Std. Error of Mean	1.796	.002723	.002741	.130580	.055079	.35212

Group		Vertical Loading Rate (bar/s)	Vertical Loading Rate (%/s)	Time to Peak Heel Rotation (s)	M1 Peak Pressure (bar)	M1 Peak Pressure (%)	Foot Balance (bar)	Peak Time (s)	Stance time (s)	Time to Peak Heel Rotation (% stance)
Injured-Shoes	Mean	65.6132	180.54	.0052341	2.53202	18.6310	-.656728	.05841	.59650	.4478
	N	144	144	144	144	144	144	144	144	134
	Std. Deviation	16.63394	46.246	.01082032	.752175	4.13241	.3296553	.013439	.018115	.66688
	Std. Error of Mean	1.38616	3.854	.00090169	.062681	.34437	.0274713	.001120	.001510	.05761
Healthy-Shoes	Mean	66.6396	177.72	.0114343	1.89235	15.2540	-.191715	.05181	.61324	1.8393
	N	168	168	168	168	168	168	168	168	168
	Std. Deviation	26.90898	58.855	.01147510	.761534	6.34637	.6069063	.023232	.023287	1.80690
	Std. Error of Mean	2.07607	4.541	.00088532	.058754	.48963	.0468238	.001792	.001797	.13941
Healthy-Boots	Mean	45.9174	130.20	.0086568	1.94609	18.3482	-.162650	.06031	.61268	1.4347
	N	125	139	141	141	140	141	141	140	141
	Std. Deviation	10.16019	79.365	.00808084	.725604	9.39181	.1576532	.035212	.070262	1.23068
	Std. Error of Mean	.90875	6.732	.00068053	.061107	.79375	.0132768	.002965	.005938	.10364
Total	Mean	60.3740	163.97	.0085989	2.11242	17.2882	-.330487	.05656	.60773	1.2896
	N	437	451	453	453	452	453	453	452	443
	Std. Deviation	21.94460	66.389	.01060723	.799410	7.06964	.4775152	.025582	.043423	1.47767
	Std. Error of Mean	1.04975	3.126	.00049837	.037560	.33253	.0224356	.001202	.002042	.07021

Table A5.1: Right foot descriptives per group

Group		Cadence (s/min)	Step time (s)	Stride time (s)	Overall Peak Pressure (bar)	Vertical Impact Peak (bar)	Vertical Impact Peak (%)
Injured-Shoes	Mean	119.70	.50186	.96805	12.87370	3.14136	24.0682
	N	141	141	141	141	141	141
	Std. Deviation	9.181	.036209	.032816	1.924822	.484275	4.24132
	Std. Error of Mean	.773	.003049	.002764	.162099	.040783	.35718
Healthy-Shoes	Mean	121.61	.50165	1.02508	10.33855	1.33162	13.0557
	N	160	172	172	172	172	172
	Std. Deviation	7.137	.045617	.037692	1.053364	.611111	5.99350
	Std. Error of Mean	.564	.003478	.002874	.080318	.046597	.45700
Healthy-Boots	Mean	109.23	.55080	1.04248	10.60534	1.64902	14.8265
	N	121	120	143	143	143	143
	Std. Deviation	4.425	.020265	.110902	1.864451	1.367662	10.79731
	Std. Error of Mean	.402	.001850	.009274	.155913	.114370	.90292
Total	Mean	117.43	.51534	1.01290	11.20611	1.99074	17.0162
	N	422	433	456	456	456	456
	Std. Deviation	8.974	.042954	.075220	1.975241	1.186370	8.84685
	Std. Error of Mean	.437	.002064	.003522	.092499	.055557	.41429

Group		Vertical Loading Rate (bar/s)	Vertical Loading Rate (%/s)	Time to Peak Heel Rotation (s)	M1 Peak Pressure (bar)	M1 Peak Pressure (%)	Foot Balance (bar)	Peak Time (s)	Stance time (s)	Time to Peak Heel Rotation (% stance)
Injured-Shoes	Mean	54.4110	161.41	.0000946	2.45142	18.9186	.765417	.05846	.58649	.0159
	N	141	141	141	141	141	141	136	141	141
	Std. Deviation	10.97615	47.545	.00079154	.615656	3.07094	.2383846	.010869	.024386	.13310
	Std. Error of Mean	.92436	4.004	.00006666	.051848	.25862	.0200756	.000932	.002054	.01121
Healthy-Shoes	Mean	24.5345	77.87	.0363360	1.98462	19.1999	-.556763	.06907	.61756	5.9816
	N	169	149	172	172	172	172	169	172	172
	Std. Deviation	16.58504	57.545	.02452852	.632894	5.93752	.5174612	.038663	.025351	4.05877
	Std. Error of Mean	1.27577	4.714	.00187028	.048258	.45273	.0394560	.002974	.001933	.30948
Healthy-Boots	Mean	29.1709	78.91	.0195005	2.00786	18.7797	-.124323	.07074	.60345	10.8503
	N	140	143	144	143	143	143	132	144	144
	Std. Deviation	23.62552	60.020	.02414689	.620078	4.91239	.5029810	.044326	.063379	66.42504
	Std. Error of Mean	1.99672	5.019	.00201224	.051854	.41080	.0420614	.003858	.005282	5.53542
Total	Mean	35.3382	105.42	.0198495	2.13625	18.9812	-.012319	.06627	.60353	5.6751
	N	450	433	457	456	456	456	437	457	457
	Std. Deviation	21.98423	67.594	.02513747	.657126	4.86974	.7074695	.035086	.042981	37.52674
	Std. Error of Mean	1.03635	3.248	.00117588	.030773	.22805	.0331303	.001678	.002011	1.75543

Table A5.2: Left foot descriptives per group

1.2 ANOVA Left/Right comparison

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Cadence (s/min)	Right	441	120.30	39.807	1.896	116.57	124.02	0	600
	Left	443	115.55	17.142	.814	113.95	117.15	0	140
	Total	884	117.92	30.697	1.032	115.89	119.95	0	600
Step time (s)	Right	453	.48606	.092568	.004349	.47752	.49461	.000	.650
	Left	455	.50627	.079966	.003749	.49890	.51363	.000	.647
	Total	908	.49619	.087024	.002888	.49052	.50186	.000	.650
Stride time (s)	Right	478	.98174	.189460	.008666	.96472	.99877	.000	1.201
	Left	478	.97941	.192874	.008822	.96208	.99675	.000	1.197
	Total	956	.98058	.191078	.006180	.96845	.99271	.000	1.201
Overall Peak Pressure (bar)	Right	478	12.28486	2.777628	.127046	12.03522	12.53450	-.568	16.521
	Left	478	11.21665	1.995380	.091267	11.03732	11.39599	5.371	16.493
	Total	956	11.75076	2.475444	.080062	11.59364	11.90787	-.568	16.521
Vertical Impact Peak (bar)	Right	478	3.12060	1.174024	.053699	3.01508	3.22611	.064	4.773
	Left	478	2.00075	1.188406	.054356	1.89394	2.10756	.064	4.177
	Total	956	2.56068	1.306791	.042265	2.47773	2.64362	.064	4.773
Vertical Impact Peak (%)	Right	477	25.1080	7.54649	.34553	24.4290	25.7869	-.41	37.58
	Left	478	17.0659	8.85255	.40491	16.2702	17.8615	-.32	36.26
	Total	955	21.0827	9.15340	.29620	20.5014	21.6640	-.41	37.58
Vertical Loading Rate (bar/s)	Right	461	60.1110	22.20409	1.03415	58.0788	62.1433	17.96	128.94
	Left	472	35.4064	21.89299	1.00771	33.4263	37.3866	.15	136.79
	Total	933	47.6131	25.26423	.82711	45.9899	49.2363	.15	136.79
Vertical Loading Rate (% /s)	Right	475	164.00	67.831	3.112	157.88	170.11	-2	395
	Left	455	106.56	70.240	3.293	100.08	113.03	0	545
	Total	930	135.89	74.726	2.450	131.08	140.70	-2	545
Time to Peak Heel Rotation (s)	Right	478	.0085956	.01056236	.00048311	.0076464	.0095449	.00000	.06670
	Left	479	.0195923	.02515766	.00114948	.0173336	.0218509	.00000	.06670
	Total	957	.0140997	.02005946	.00064843	.0128272	.0153722	.00000	.06670
M1 Peak Pressure (bar)	Right	478	2.11060	.793808	.036308	2.03926	2.18195	.094	3.839
	Left	478	2.13874	.656653	.030035	2.07973	2.19776	.538	3.615
	Total	956	2.12467	.728220	.023552	2.07845	2.17089	.094	3.839
M1 Peak Pressure (%)	Right	477	17.2998	7.09731	.32496	16.6613	17.9384	-17.65	37.95
	Left	478	18.9877	4.83322	.22107	18.5533	19.4221	8.65	34.27
	Total	955	18.1446	6.12585	.19823	17.7556	18.5336	-17.65	37.95
Foot Balance (bar)	Right	478	-.329950	.4772214	.0218276	-.372840	-.287059	-1.4510	.6439
	Left	478	-.005201	.7079302	.0323800	-.068826	.058424	-1.0778	1.3317
	Total	956	-.167575	.6248713	.0202098	-.207236	-.127914	-1.4510	1.3317
Peak Time (s)	Right	478	.05668	.025931	.001186	.05435	.05901	.000	.133
	Left	459	.06712	.039284	.001834	.06352	.07072	.000	.460
	Total	937	.06180	.033542	.001096	.05964	.06395	.000	.460
Stance time (s)	Right	477	.60906	.050106	.002294	.60456	.61357	.140	1.181
	Left	479	.60366	.042526	.001943	.59984	.60747	.007	.667
	Total	956	.60635	.046517	.001504	.60340	.60931	.007	1.181
Time to Peak Heel Rotation (% stance)	Right	468	1.2962	1.48042	.06843	1.1617	1.4307	.00	6.25
	Left	479	5.5471	36.67067	1.67553	2.2548	8.8394	.00	800.00
	Total	947	3.4463	26.17403	.85054	1.7772	5.1155	.00	800.00

Table A5.3: Descriptives per side

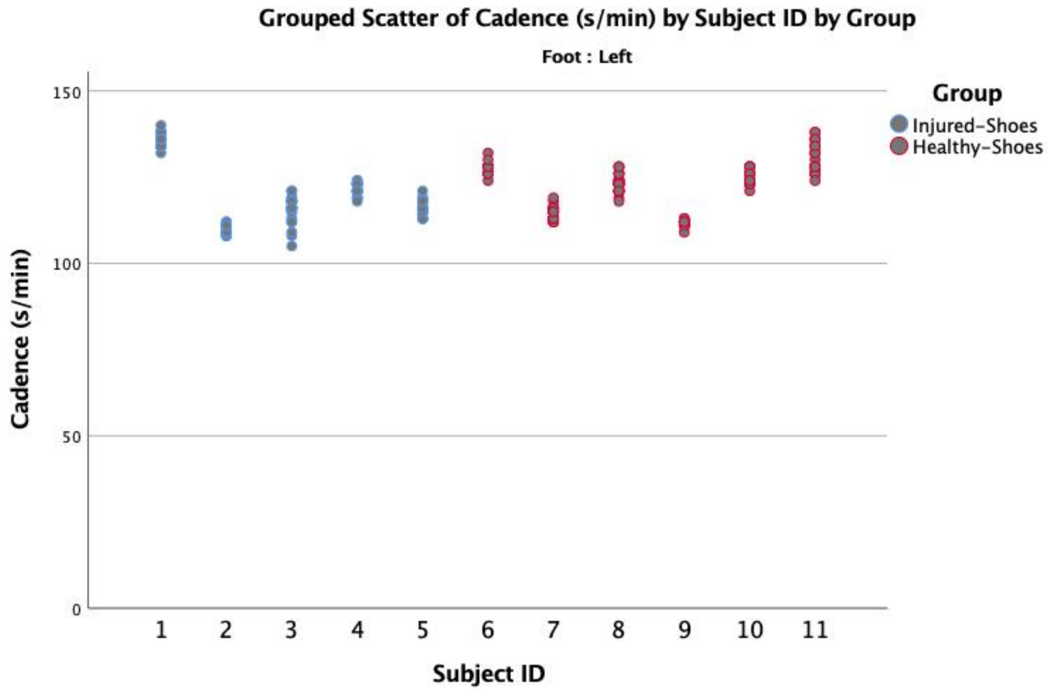
ANOVA

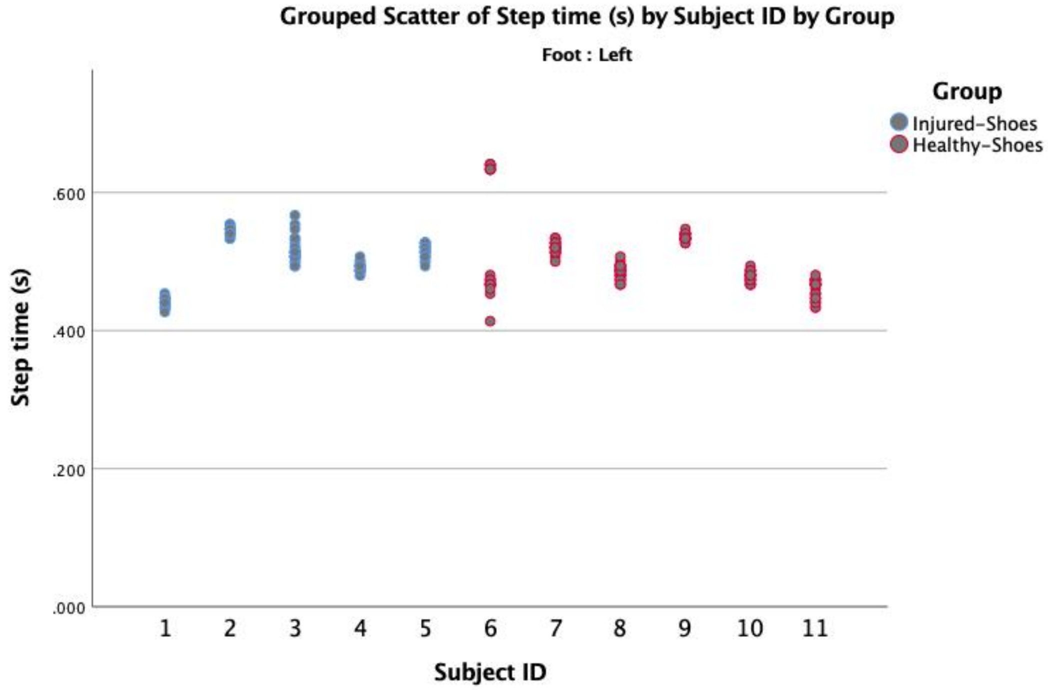
		Sum of Squares	df	Mean Square	F	Sig.
Cadence (s/min)	Between Groups	4979.544	1	4979.544	5.310	.021
	Within Groups	827093.590	882	937.748		
	Total	832073.133	883			
Step time (s)	Between Groups	.093	1	.093	12.389	.000
	Within Groups	6.776	906	.007		
	Total	6.869	907			
Stride time (s)	Between Groups	.001	1	.001	.036	.851
	Within Groups	34.866	954	.037		
	Total	34.868	955			
Overall Peak Pressure (bar)	Between Groups	272.716	1	272.716	46.631	.000
	Within Groups	5579.354	954	5.848		
	Total	5852.070	955			
Vertical Impact Peak (bar)	Between Groups	299.721	1	299.721	214.804	.000
	Within Groups	1331.137	954	1.395		
	Total	1630.857	955			
Vertical Impact Peak (%)	Between Groups	15441.360	1	15441.360	228.187	.000
	Within Groups	64489.331	953	67.670		
	Total	79930.691	954			
Vertical Loading Rate (bar/s)	Between Groups	142336.742	1	142336.742	292.825	.000
	Within Groups	452541.615	931	486.081		
	Total	594878.357	932			
Vertical Loading Rate (% /s)	Between Groups	766776.076	1	766776.076	160.959	.000
	Within Groups	4420791.48	928	4763.784		
	Total	5187567.55	929			
Time to Peak Heel Rotation (s)	Between Groups	.029	1	.029	77.666	.000
	Within Groups	.356	955	.000		
	Total	.385	956			
M1 Peak Pressure (bar)	Between Groups	.189	1	.189	.357	.551
	Within Groups	506.251	954	.531		
	Total	506.441	955			
M1 Peak Pressure (%)	Between Groups	680.177	1	680.177	18.457	.000
	Within Groups	35119.715	953	36.852		
	Total	35799.892	954			
Foot Balance (bar)	Between Groups	25.205	1	25.205	69.160	.000
	Within Groups	347.688	954	.364		
	Total	372.893	955			
Peak Time (s)	Between Groups	.026	1	.026	23.224	.000
	Within Groups	1.028	935	.001		
	Total	1.053	936			
Stance time (s)	Between Groups	.007	1	.007	3.238	.072
	Within Groups	2.059	954	.002		
	Total	2.066	955			
Time to Peak Heel Rotation (% stance)	Between Groups	4277.491	1	4277.491	6.279	.012
	Within Groups	643808.102	945	681.278		
	Total	648085.593	946			

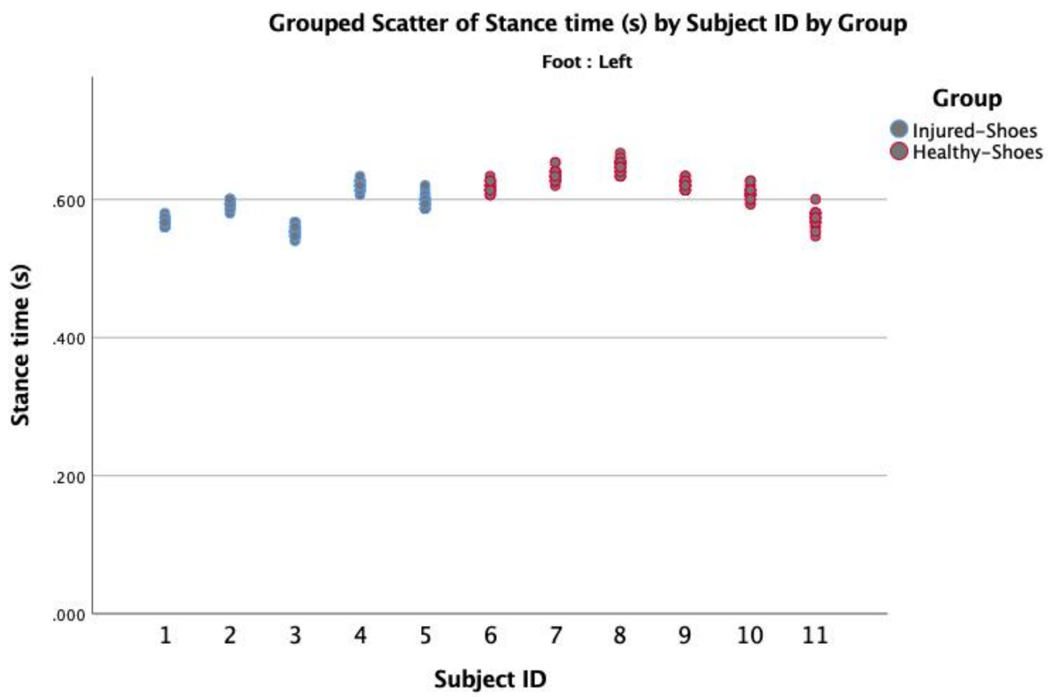
Table A5.4: ANOVA

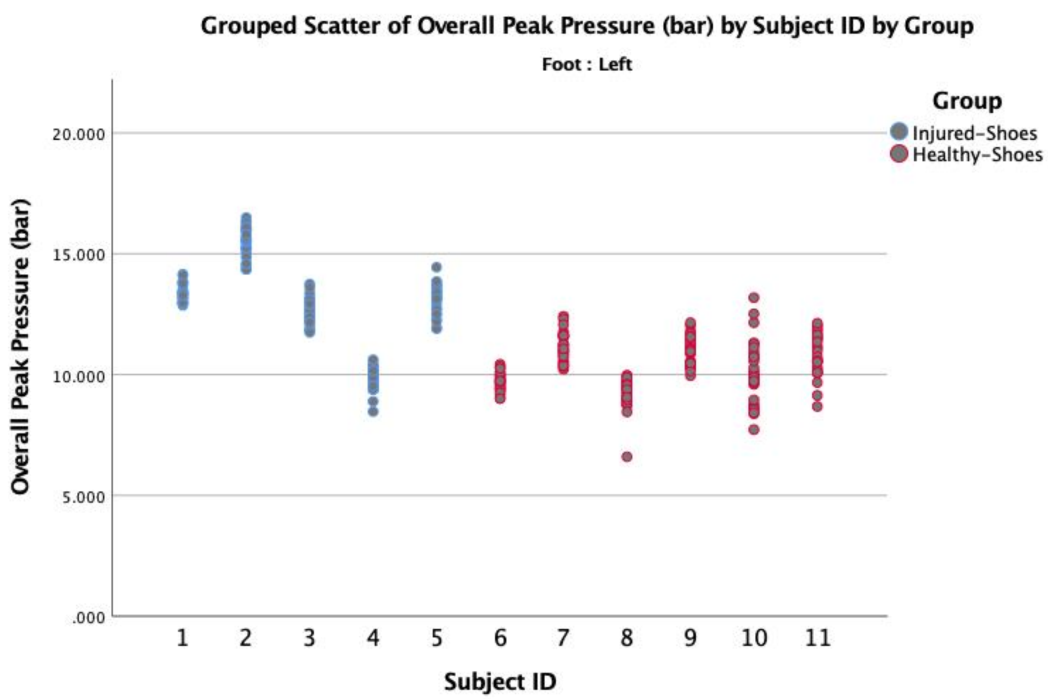
2. Study 2. Injured vs Control

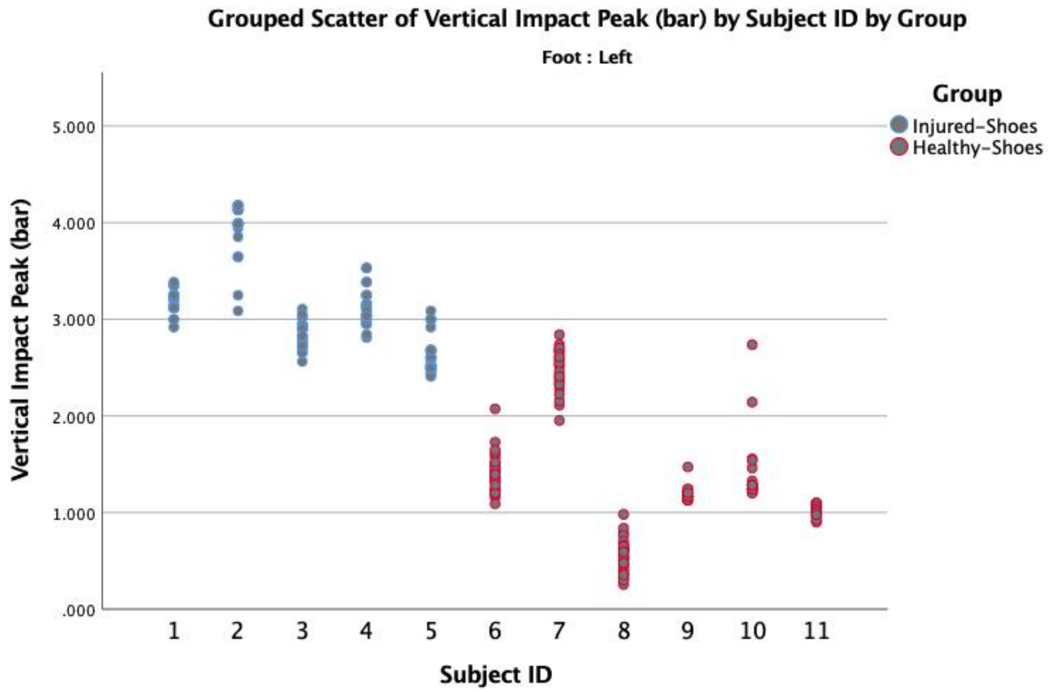
2.1 Scatter plots

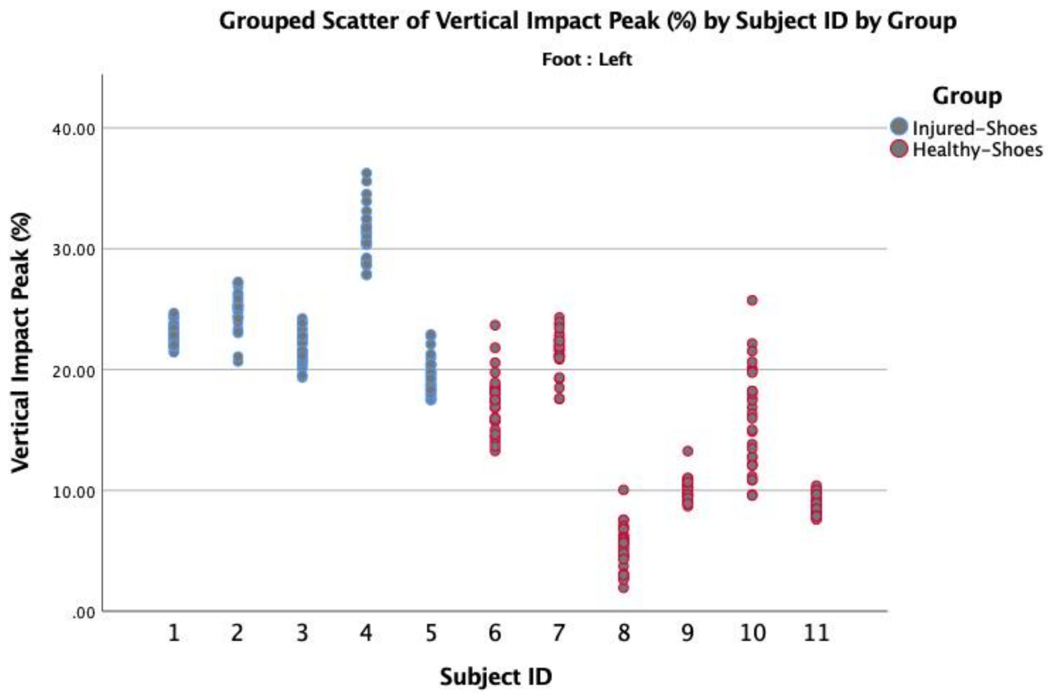


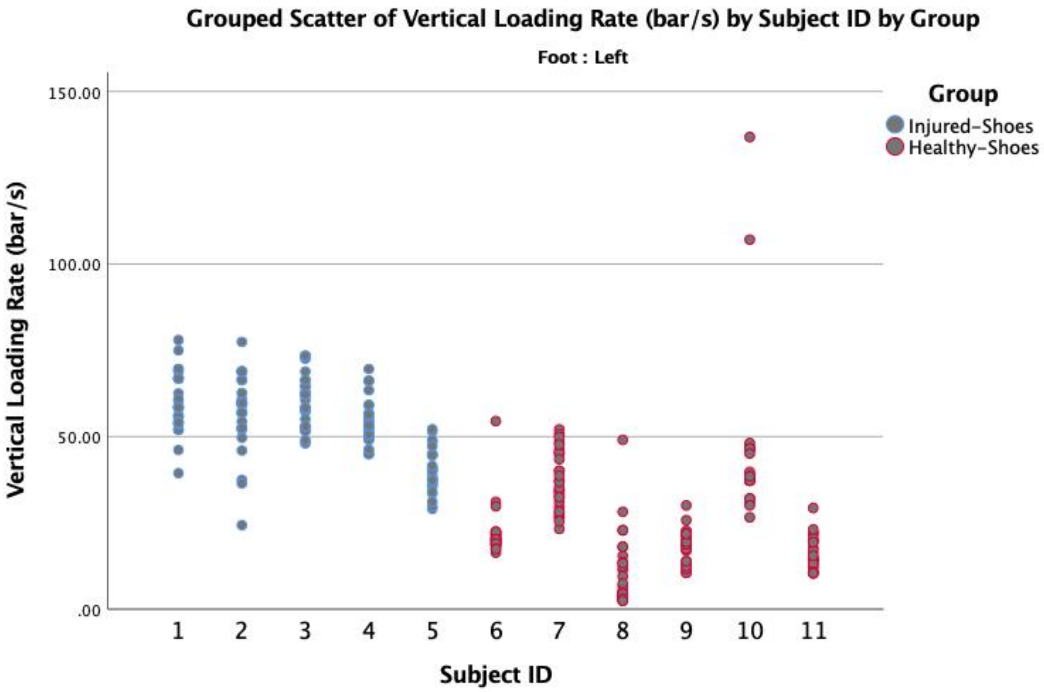


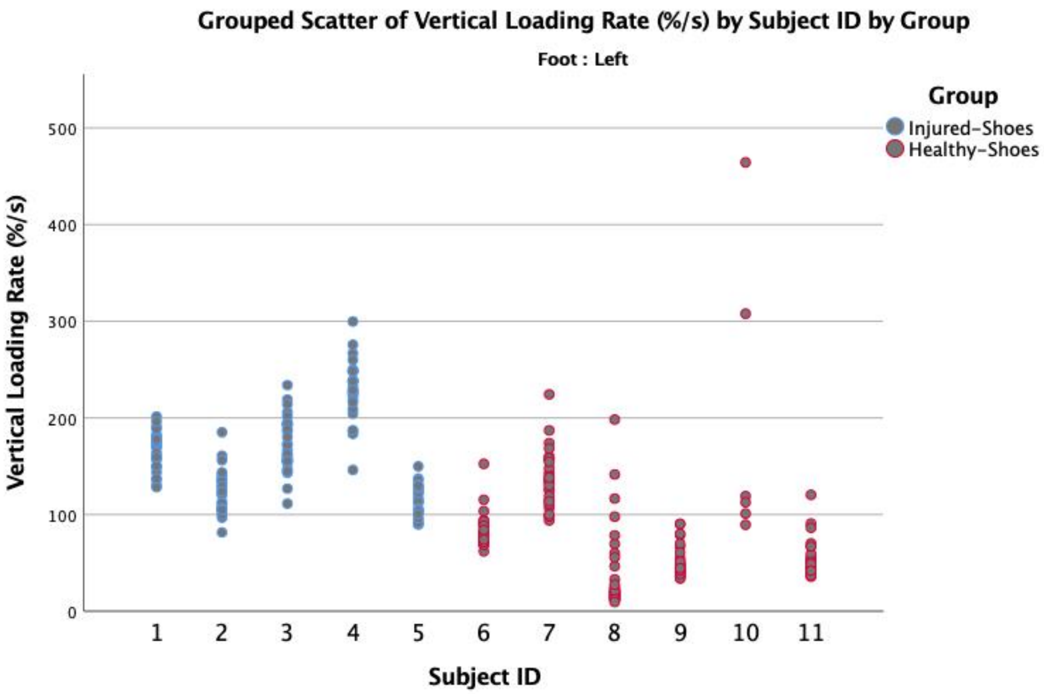

Grouped Scatter of Stance time (s) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Stance time (s)
.600
.400
.200
.000
1
2
3
4
5
6
7
8
9
10
11
Subject ID

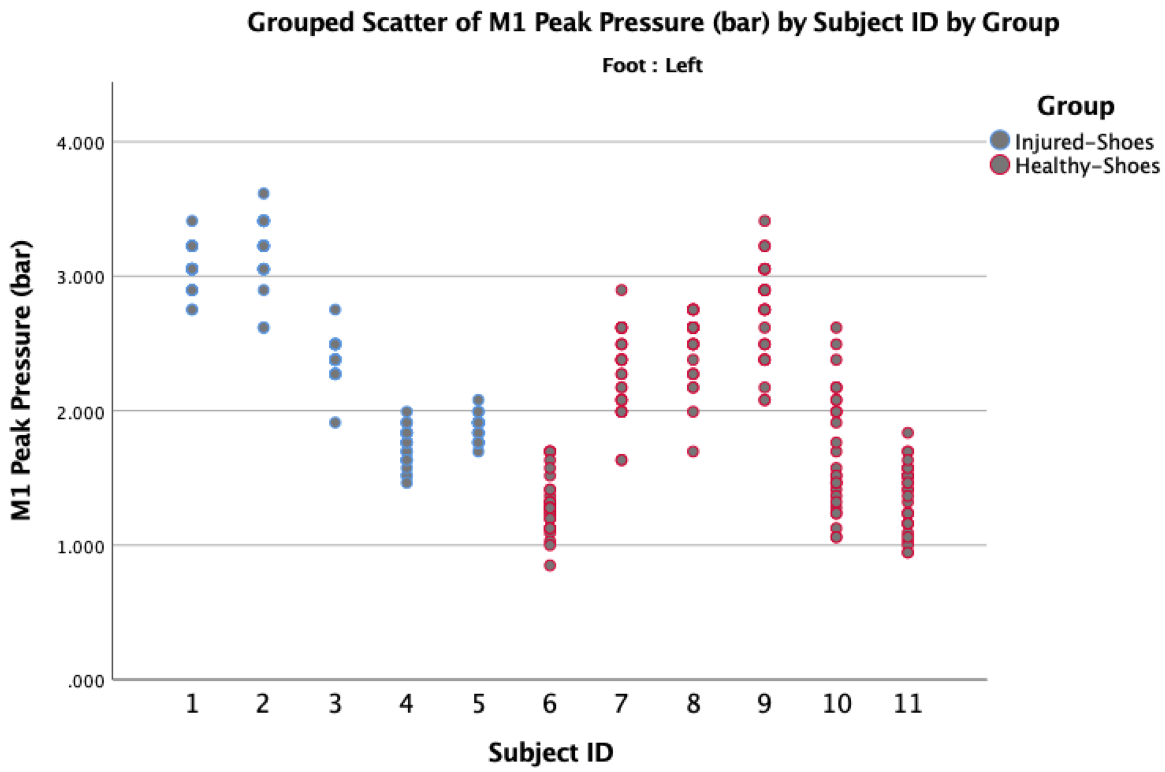

Grouped Scatter of Overall Peak Pressure (bar) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Overall Peak Pressure (bar)
20.000
15.000
10.000
5.000
.000
1
2
3
4
5
6
7
8
9
10
11
Subject ID

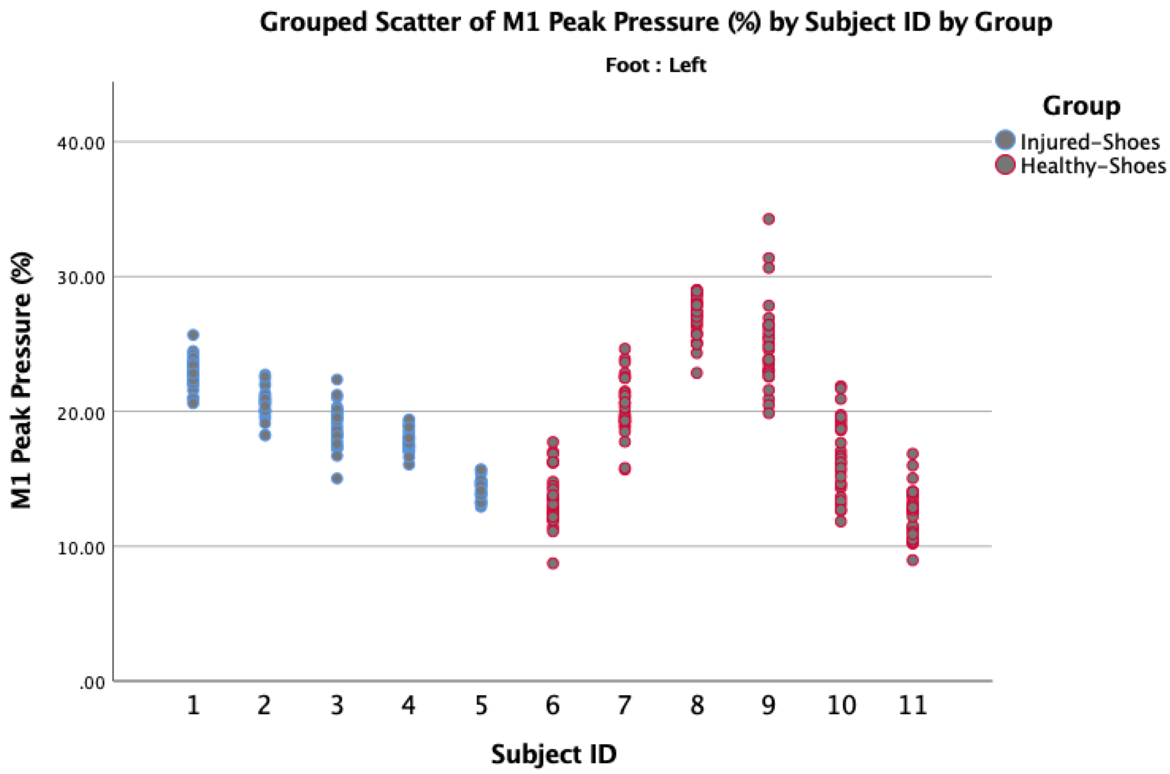

Grouped Scatter of Vertical Impact Peak (bar) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Vertical Impact Peak (bar)
5.000
4.000
3.000
2.000
1.000
.000
1 2 3 4 5 6 7 8 9 10 11
Subject ID

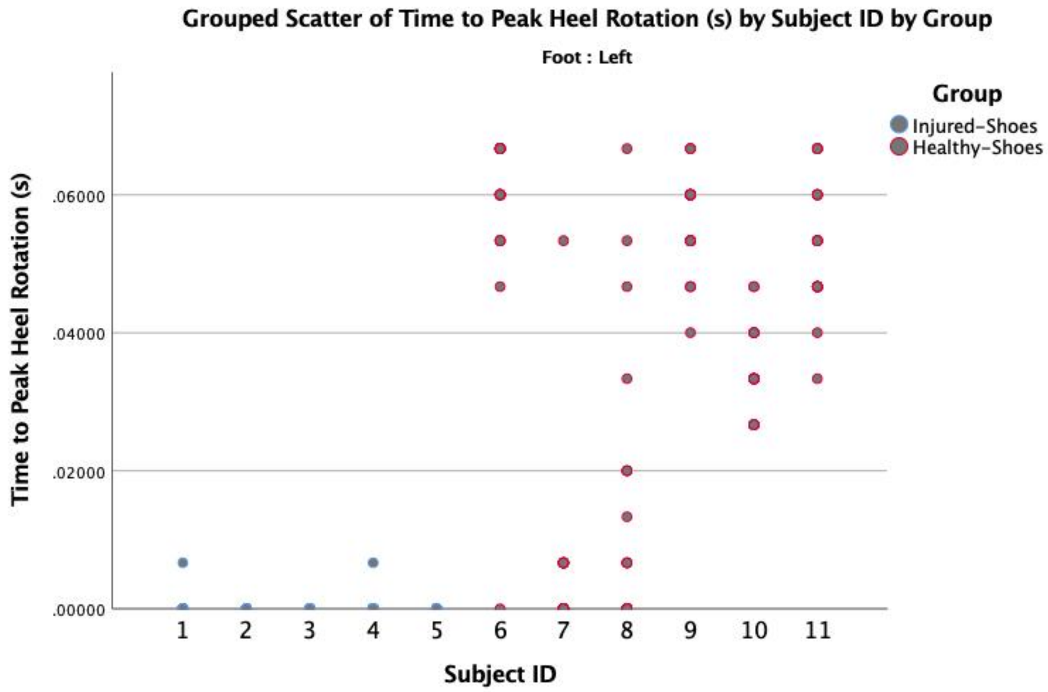

Grouped Scatter of Vertical Impact Peak (%) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Vertical Impact Peak (%)
40.00
30.00
20.00
10.00
.00
1 2 3 4 5 6 7 8 9 10 11
Subject ID

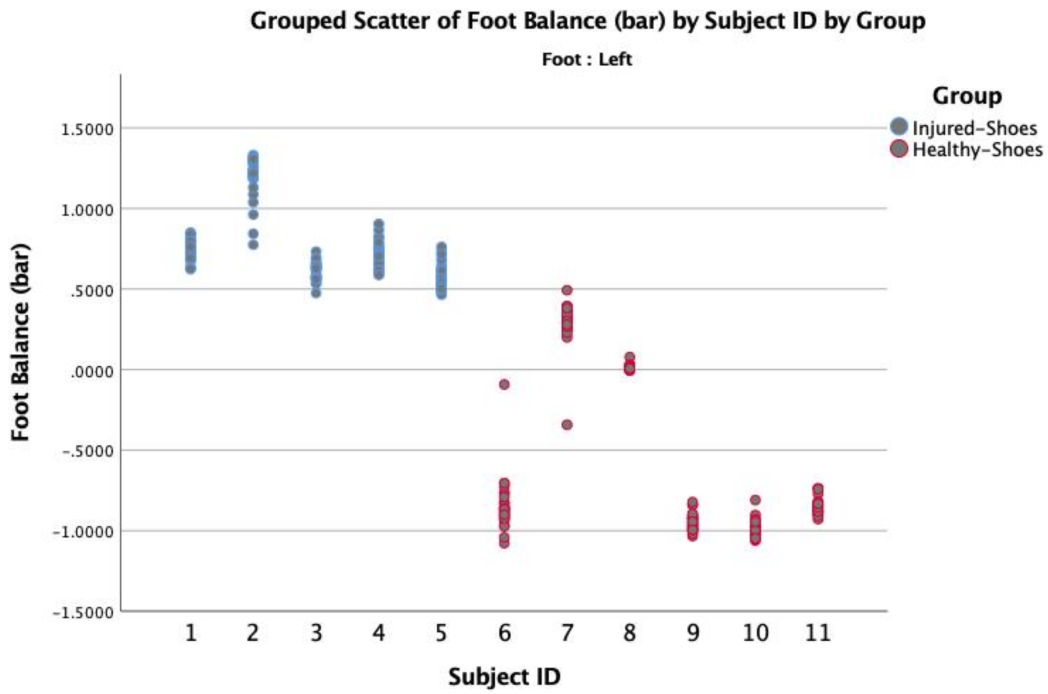

Grouped Scatter of Vertical Loading Rate (bar/s) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Vertical Loading Rate (bar/s)
150.00
100.00
50.00
.00
1
2
3
4
5
6
7
8
9
10
11
Subject ID


Grouped Scatter of Vertical Loading Rate (%/s) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Vertical Loading Rate (%/s)
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
11
Subject ID


Grouped Scatter of M1 Peak Pressure (bar) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
M1 Peak Pressure (bar)
4.000
3.000
2.000
1.000
.000
1
2
3
4
5
6
7
8
9
10
11
Subject ID


Grouped Scatter of M1 Peak Pressure (%) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
M1 Peak Pressure (%)
40.00
30.00
20.00
10.00
.00
1
2
3
4
5
6
7
8
9
10
11
Subject ID


Grouped Scatter of Time to Peak Heel Rotation (s) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Time to Peak Heel Rotation (s)
.06000
.04000
.02000
.00000
1
2
3
4
5
6
7
8
9
10
11
Subject ID


Grouped Scatter of Foot Balance (bar) by Subject ID by Group
Foot : Left
Group
Injured-Shoes
Healthy-Shoes
Foot Balance (bar)
1.5000
1.0000
.5000
.0000
-.5000
-1.0000
-1.5000
1
2
3
4
5
6
7
8
9
10
11
Subject ID

2.2 ANOVA

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Cadence (s/min)	Injured-Shoes	141	119.70	9.181	.773	118.17	121.23	105	140
	Healthy-Shoes	160	121.61	7.137	.564	120.50	122.73	109	138
	Total	301	120.72	8.201	.473	119.79	121.65	105	140
Step time (s)	Injured-Shoes	141	.50186	.036209	.003049	.49583	.50789	.427	.567
	Healthy-Shoes	172	.50165	.045617	.003478	.49478	.50851	.414	.640
	Total	313	.50174	.041579	.002350	.49712	.50637	.414	.640
Stride time (s)	Injured-Shoes	141	.96805	.032816	.002764	.96259	.97351	.907	1.027
	Healthy-Shoes	172	1.02508	.037692	.002874	1.01941	1.03075	.907	1.094
	Total	313	.99939	.045492	.002571	.99433	1.00445	.907	1.094
Overall Peak Pressure (bar)	Injured-Shoes	141	12.87370	1.924822	.162099	12.55322	13.19418	8.468	16.493
	Healthy-Shoes	172	10.33855	1.053364	.080318	10.18001	10.49709	6.598	13.182
	Total	313	11.48058	1.966391	.111147	11.26189	11.69927	6.598	16.493
Vertical Impact Peak (bar)	Injured-Shoes	141	3.14136	.484275	.040783	3.06073	3.22199	2.409	4.177
	Healthy-Shoes	172	1.33162	.611111	.046597	1.23964	1.42359	.254	2.840
	Total	313	2.14687	1.059847	.059906	2.02900	2.26474	.254	4.177
Vertical Impact Peak (%)	Injured-Shoes	141	24.0682	4.24132	.35718	23.3620	24.7744	17.48	36.26
	Healthy-Shoes	172	13.0557	5.99350	.45700	12.1536	13.9578	1.94	25.73
	Total	313	18.0166	7.60773	.43001	17.1705	18.8627	1.94	36.26
Vertical Loading Rate (bar/s)	Injured-Shoes	141	54.4110	10.97615	.92436	52.5835	56.2385	24.36	77.97
	Healthy-Shoes	169	24.5345	16.58504	1.27577	22.0159	27.0531	2.41	136.79
	Total	310	38.1235	20.64414	1.17251	35.8164	40.4306	2.41	136.79
Vertical Loading Rate (% /s)	Injured-Shoes	141	161.41	47.545	4.004	153.50	169.33	82	300
	Healthy-Shoes	149	77.87	57.545	4.714	68.56	87.19	10	464
	Total	290	118.49	67.382	3.957	110.70	126.28	10	464
Time to Peak Heel Rotation (s)	Injured-Shoes	141	.0000946	.00079154	.00006666	-.0000372	.0002264	.00000	.00667
	Healthy-Shoes	172	.0363360	.02452852	.00187028	.0326442	.0400278	.00000	.06670
	Total	313	.0200100	.02561662	.00144794	.0171610	.0228590	.00000	.06670
M1 Peak Pressure (%)	Injured-Shoes	141	18.9186	3.07094	.25862	18.4073	19.4299	12.93	25.68
	Healthy-Shoes	172	19.1999	5.93752	.45273	18.3063	20.0936	8.73	34.27
	Total	313	19.0732	4.85524	.27443	18.5332	19.6132	8.73	34.27
Foot Balance (bar)	Injured-Shoes	141	.765417	.2383846	.0200756	.725726	.805108	.4649	1.3317
	Healthy-Shoes	172	-.556763	.5174612	.0394560	-.634646	-.478879	-1.0778	.4929
	Total	313	.038852	.7787141	.0440155	-.047753	.125457	-1.0778	1.3317
Peak Time (s)	Injured-Shoes	136	.05846	.010869	.000932	.05662	.06030	.040	.100
	Healthy-Shoes	169	.06907	.038663	.002974	.06320	.07494	.013	.213
	Total	305	.06434	.030107	.001724	.06095	.06773	.013	.213
Stance time (s)	Injured-Shoes	141	.58649	.024386	.002054	.58243	.59055	.540	.634
	Healthy-Shoes	172	.61756	.025351	.001933	.61374	.62138	.547	.667
	Total	313	.60356	.029307	.001657	.60030	.60682	.540	.667
Time to Peak Heel Rotation (% stance)	Injured-Shoes	141	.0159	.13310	.01121	-.0063	.0380	.00	1.18
	Healthy-Shoes	172	5.9816	4.05877	.30948	5.3707	6.5925	.00	12.05
	Total	313	3.2942	4.22789	.23897	2.8239	3.7644	.00	12.05

a. Foot = Left

ANOVA[a]

		Sum of Squares	df	Mean Square	F	Sig.
Cadence (s/min)	Between Groups	273.532	1	273.532	4.110	.044
	Within Groups	19901.464	299	66.560		
	Total	20174.997	300			
Step time (s)	Between Groups	.000	1	.000	.002	.964
	Within Groups	.539	311	.002		
	Total	.539	312			
Stride time (s)	Between Groups	.252	1	.252	199.062	.000
	Within Groups	.394	311	.001		
	Total	.646	312			
Overall Peak Pressure (bar)	Between Groups	497.979	1	497.979	218.613	.000
	Within Groups	708.429	311	2.278		
	Total	1206.408	312			
Vertical Impact Peak (bar)	Between Groups	253.768	1	253.768	816.200	.000
	Within Groups	96.694	311	.311		
	Total	350.462	312			
Vertical Impact Peak (%)	Between Groups	9396.673	1	9396.673	337.412	.000
	Within Groups	8661.110	311	27.849		
	Total	18057.783	312			
Vertical Loading Rate (bar/s)	Between Groups	68612.463	1	68612.463	335.028	.000
	Within Groups	63077.312	308	204.796		
	Total	131689.774	309			
Vertical Loading Rate (% /s)	Between Groups	505596.031	1	505596.031	180.533	.000
	Within Groups	806563.181	288	2800.567		
	Total	1312159.21	289			
Time to Peak Heel Rotation (s)	Between Groups	.102	1	.102	307.372	.000
	Within Groups	.103	311	.000		
	Total	.205	312			
M1 Peak Pressure (bar)	Between Groups	16.884	1	16.884	43.195	.000
	Within Groups	121.559	311	.391		
	Total	138.443	312			
M1 Peak Pressure (%)	Between Groups	6.133	1	6.133	.260	.611
	Within Groups	7348.749	311	23.629		
	Total	7354.883	312			
Foot Balance (bar)	Between Groups	135.452	1	135.452	783.820	.000
	Within Groups	53.744	311	.173		
	Total	189.195	312			
Peak Time (s)	Between Groups	.008	1	.008	9.620	.002
	Within Groups	.267	303	.001		
	Total	.276	304			
Stance time (s)	Between Groups	.075	1	.075	120.467	.000
	Within Groups	.193	311	.001		
	Total	.268	312			
Time to Peak Heel Rotation (% stance)	Between Groups	2757.551	1	2757.551	304.170	.000
	Within Groups	2819.469	311	9.066		
	Total	5577.020	312			

a. Foot = Left

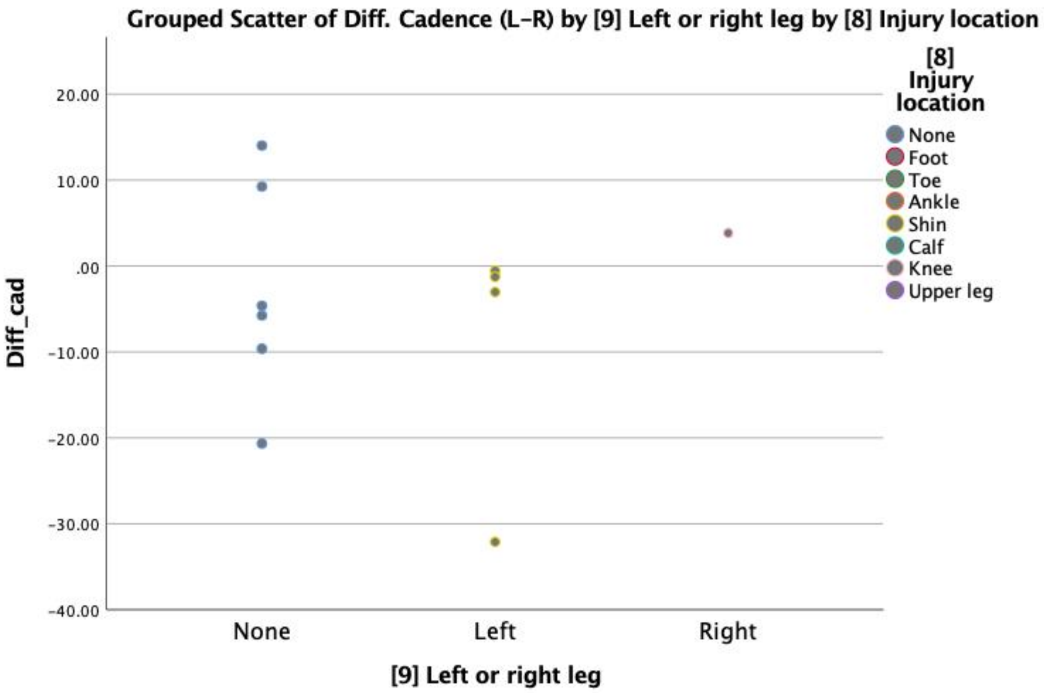
2.3 Effect sizes

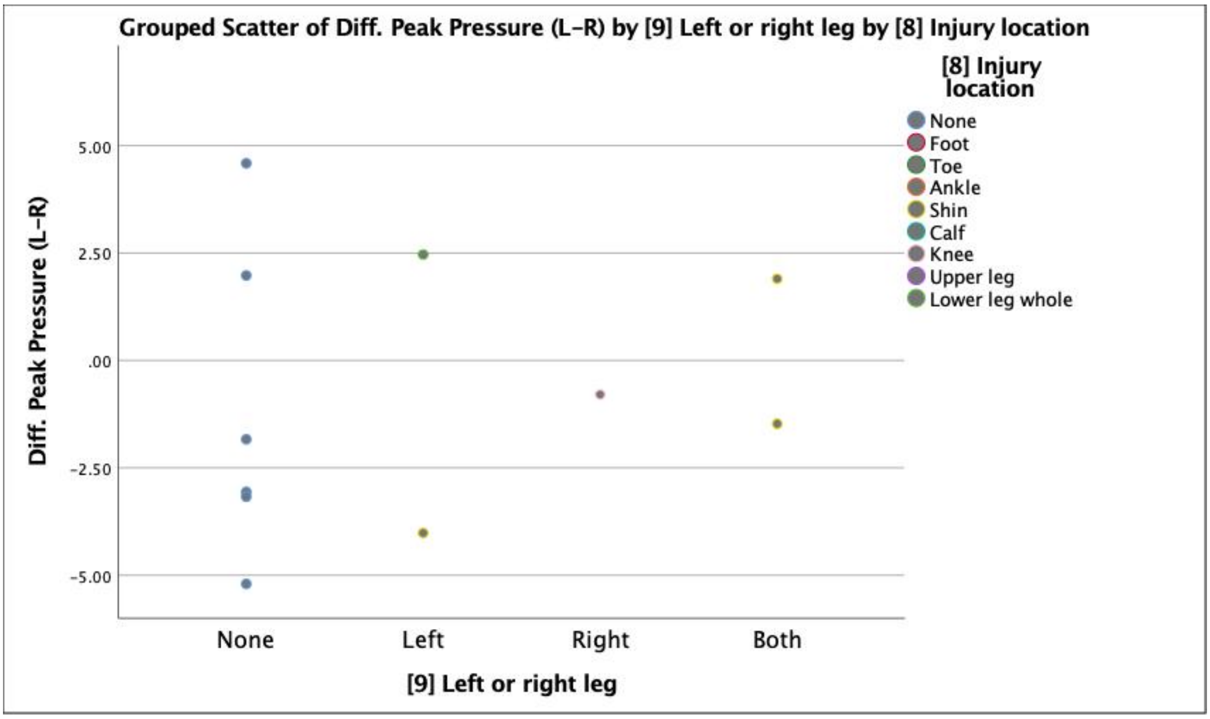
Measures of Association[a]

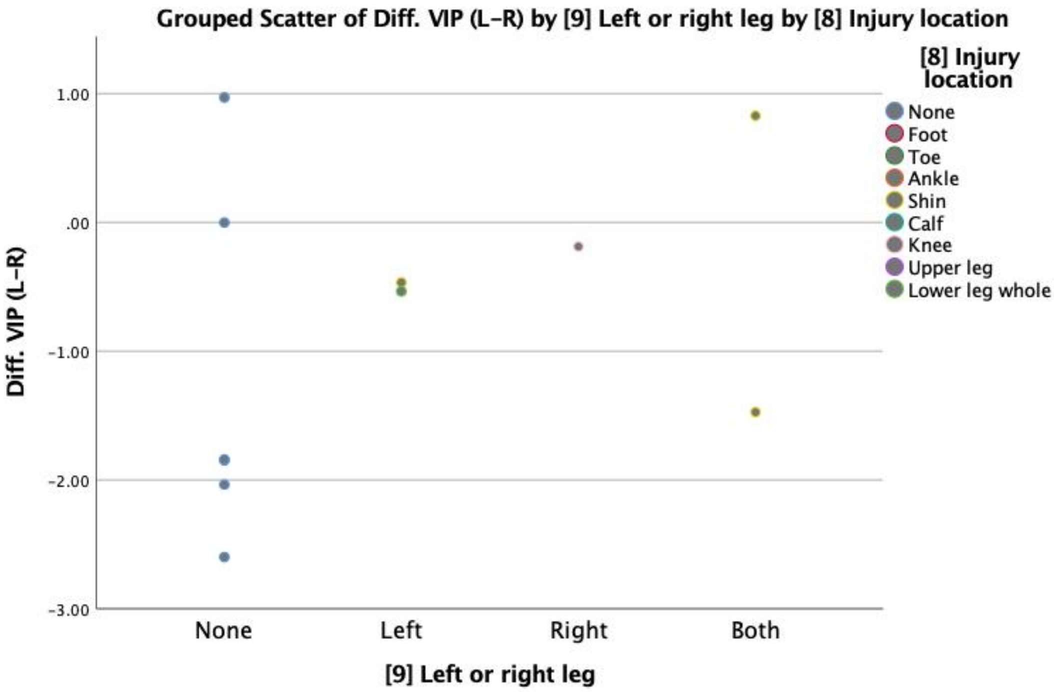
	Eta	Eta Squared
Cadence (s/min) * Group	.116	.014
Step time (s) * Group	.003	.000
Stride time (s) * Group	.625	.390
Overall Peak Pressure (bar) * Group	.642	.413
Vertical Impact Peak (bar) * Group	.851	.724
Vertical Impact Peak (%) * Group	.721	.520
Vertical Loading Rate (bar/s) * Group	.722	.521
Vertical Loading Rate (% /s) * Group	.621	.385
Time to Peak Heel Rotation (s) * Group	.705	.497
Time to Peak Heel Rotation (% stance) * Group	.703	.494
M1 Peak Pressure (bar) * Group	.349	.122
M1 Peak Pressure (%) * Group	.029	.001
Foot Balance (bar) * Group	.846	.716
Peak Time (s) * Group	.175	.031
Stance time (s) * Group	.528	.279

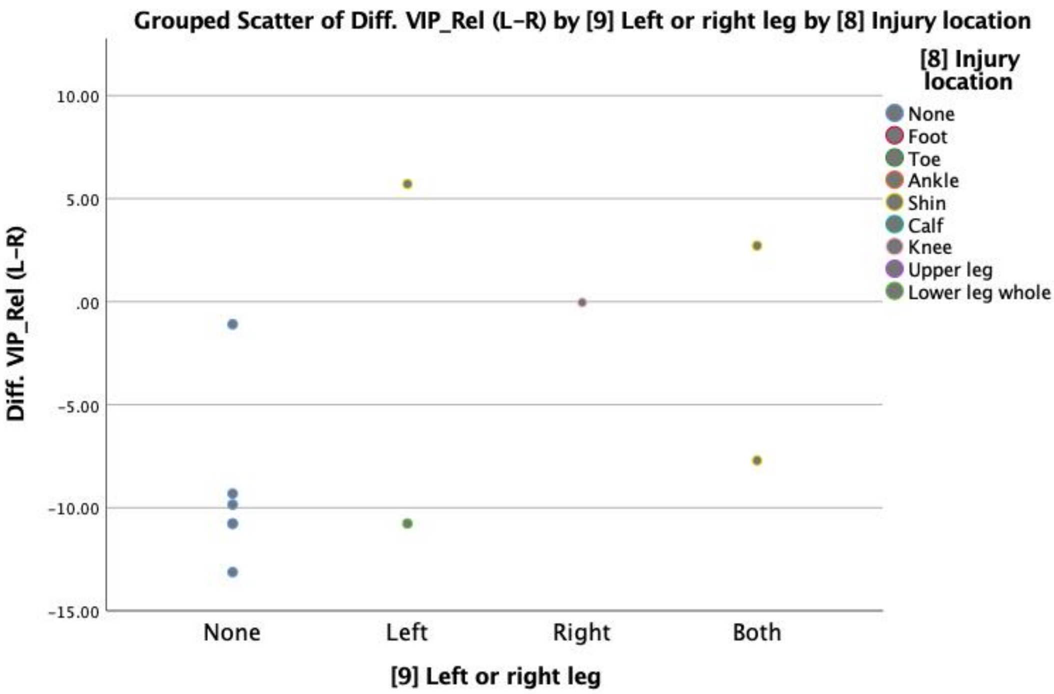
a. Foot = Left

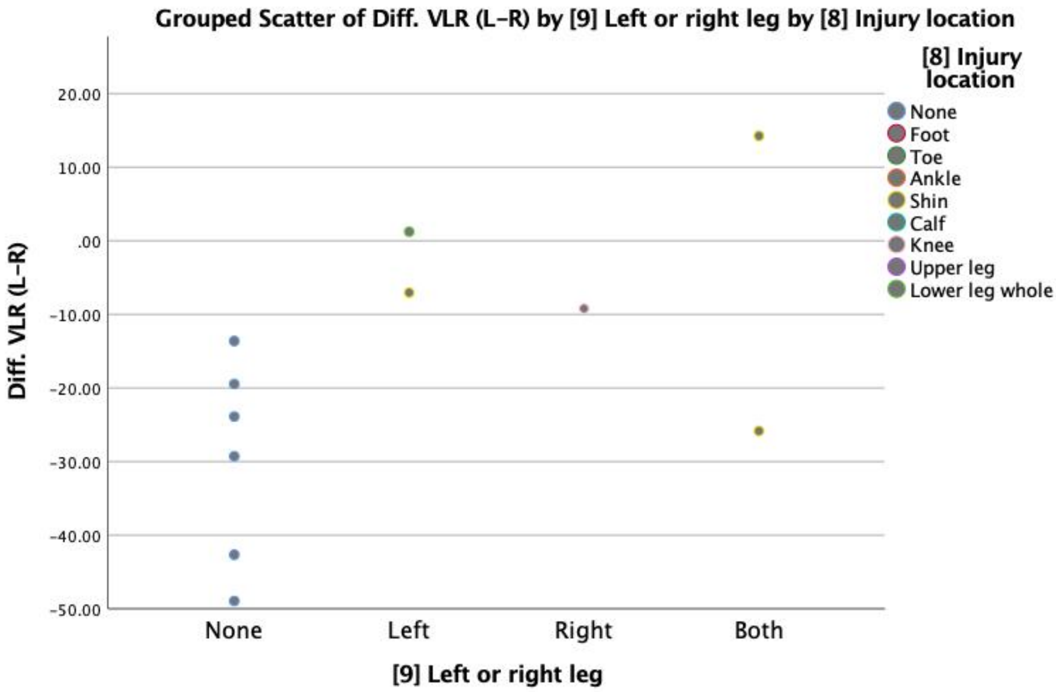
2.4 Injury location correlation

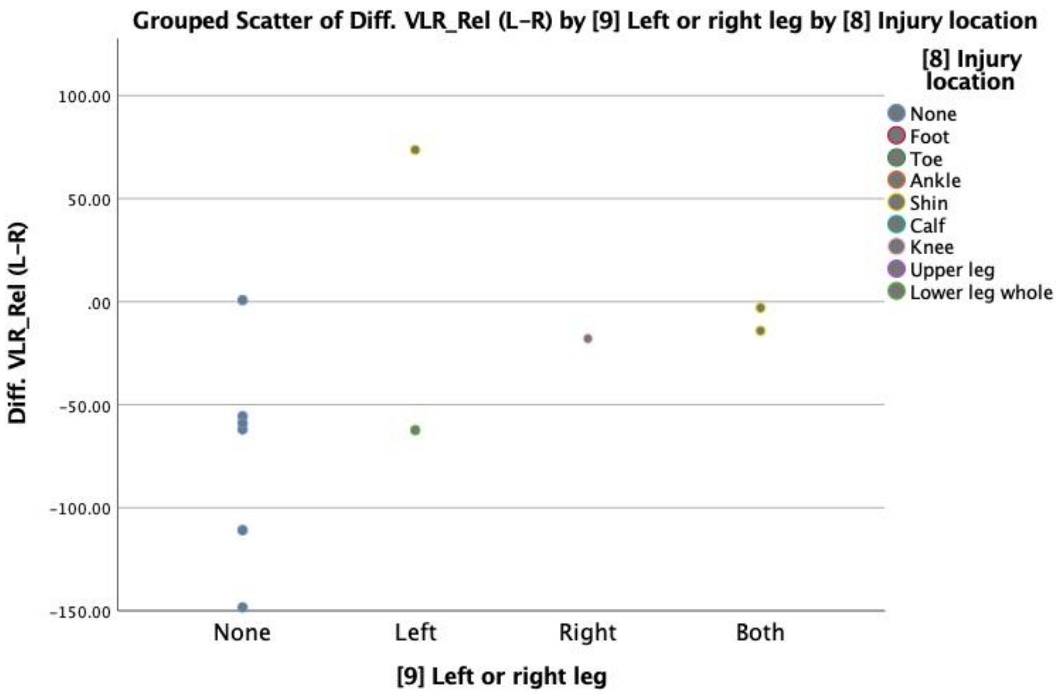


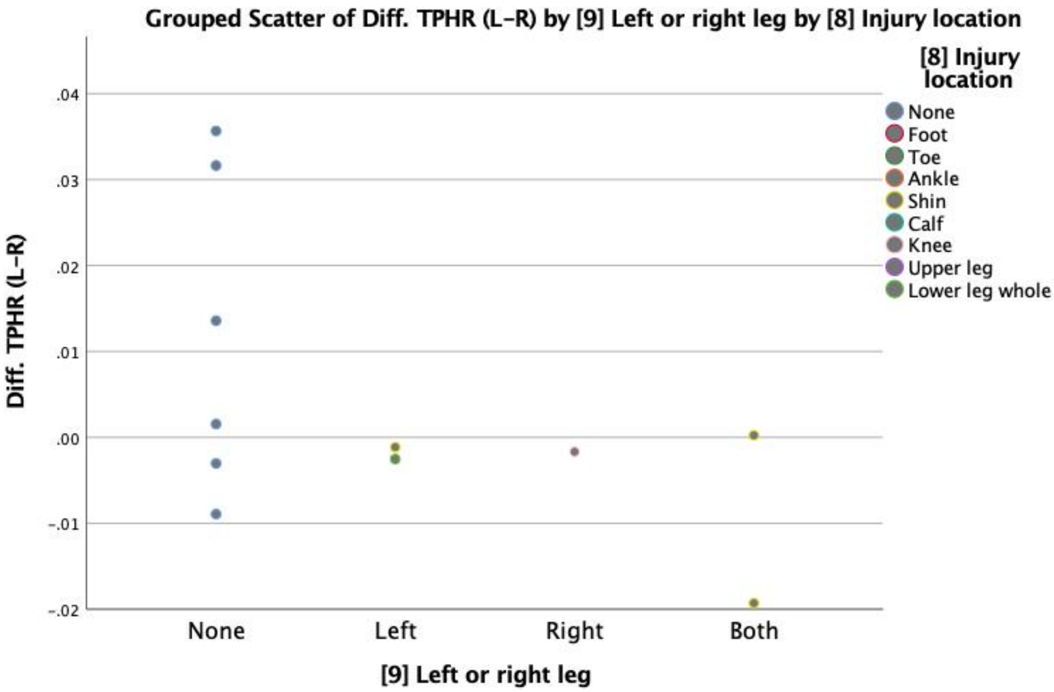



Grouped Scatter of Diff. VIP (L-R) by [9] Left or right leg by [8] Injury location
Diff. VIP (L-R)
1.00
.00
-1.00
-2.00
-3.00
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole

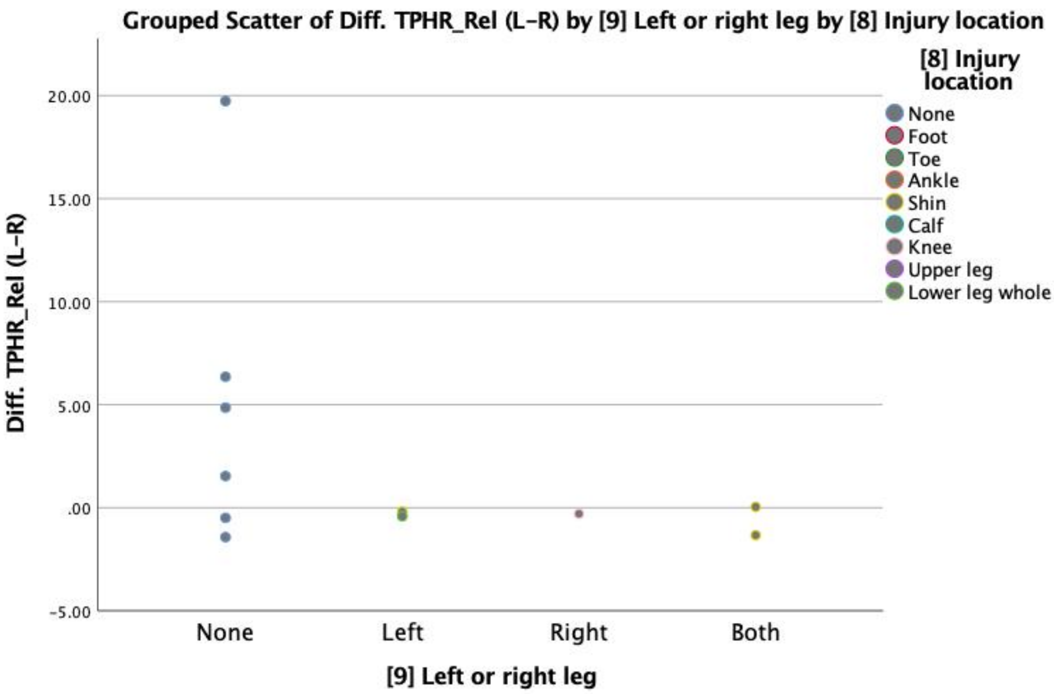

Grouped Scatter of Diff. VIP_Rel (L-R) by [9] Left or right leg by [8] Injury location
Diff. VIP_Rel (L-R)
10.00
5.00
.00
-5.00
-10.00
-15.00
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole


Grouped Scatter of Diff. VLR (L-R) by [9] Left or right leg by [8] Injury location
Diff. VLR (L-R)
20.00
10.00
.00
-10.00
-20.00
-30.00
-40.00
-50.00
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole

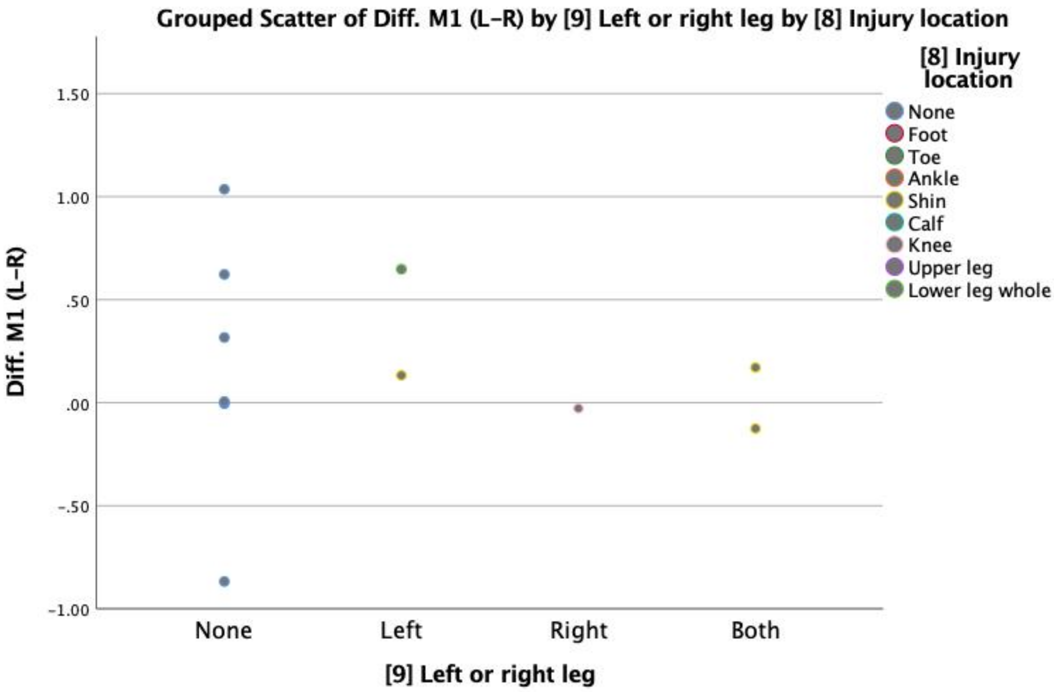

Grouped Scatter of Diff. VLR_Rel (L-R) by [9] Left or right leg by [8] Injury location
Diff. VLR_Rel (L-R)
100.00
50.00
.00
-50.00
-100.00
-150.00
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole

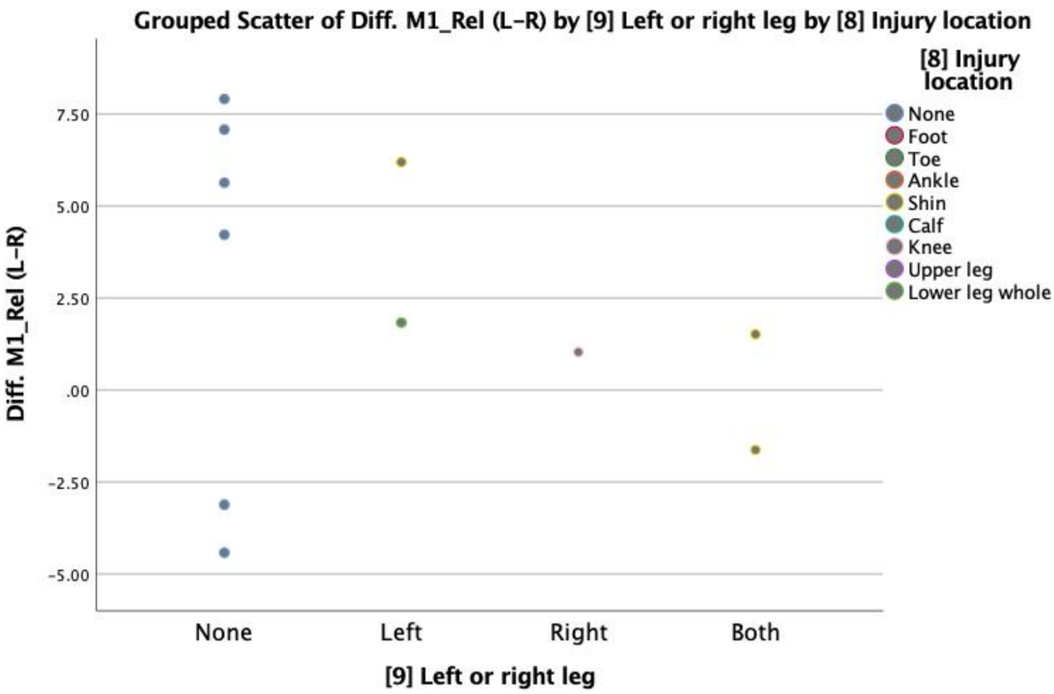


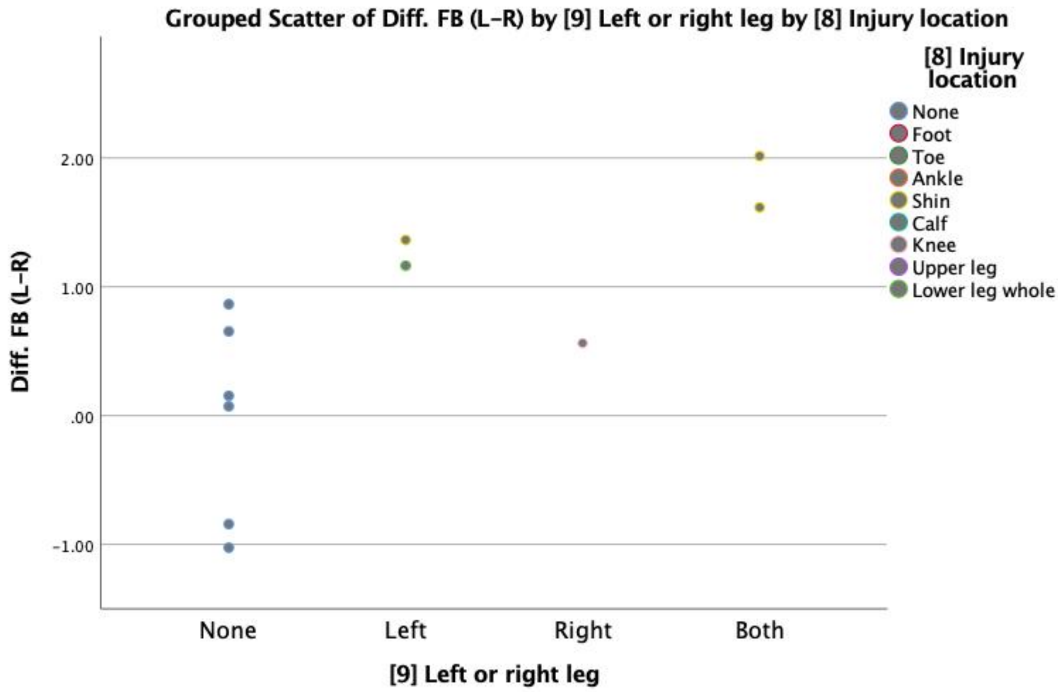
Grouped Scatter of Diff. TPHR (L-R) by [9] Left or right leg by [8] Injury location
Diff. TPHR (L-R)
.04
.03
.02
.01
.00
-.01
-.02
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole

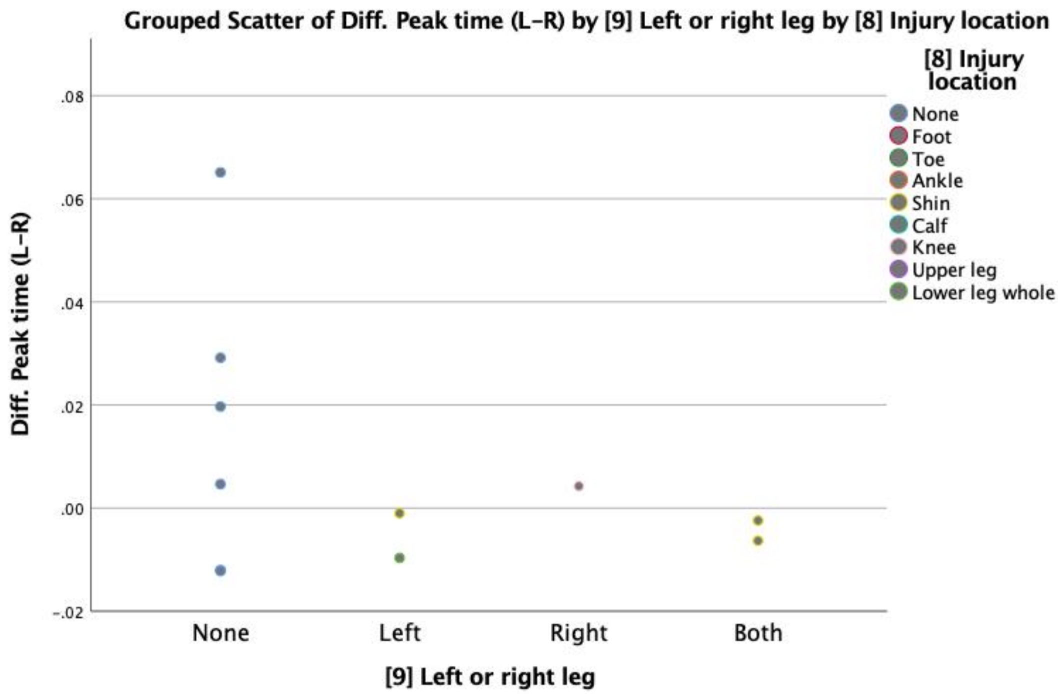


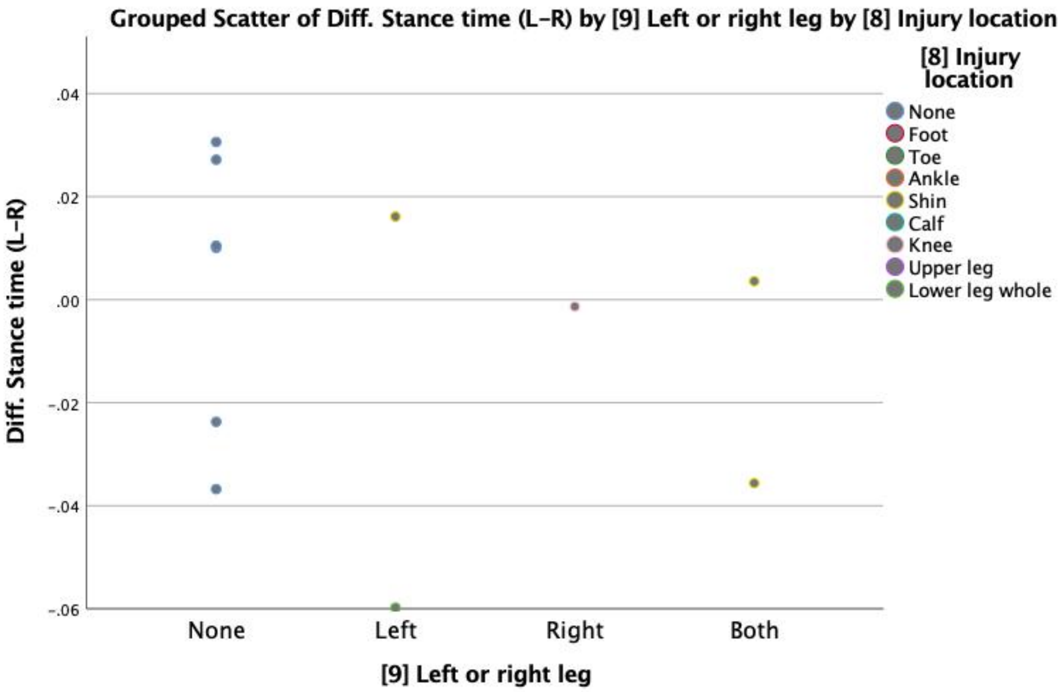
Grouped Scatter of Diff. TPHR_Rel (L-R) by [9] Left or right leg by [8] Injury location
Diff. TPHR_Rel (L-R)
20.00
15.00
10.00
5.00
.00
-5.00
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole


Grouped Scatter of Diff. M1 (L-R) by [9] Left or right leg by [8] Injury location
Diff. M1 (L-R)
1.50
1.00
.50
.00
-.50
-1.00
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole


Grouped Scatter of Diff. M1_Rel (L-R) by [9] Left or right leg by [8] Injury location
Diff. M1_Rel (L-R)
7.50
5.00
2.50
.00
-2.50
-5.00
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole

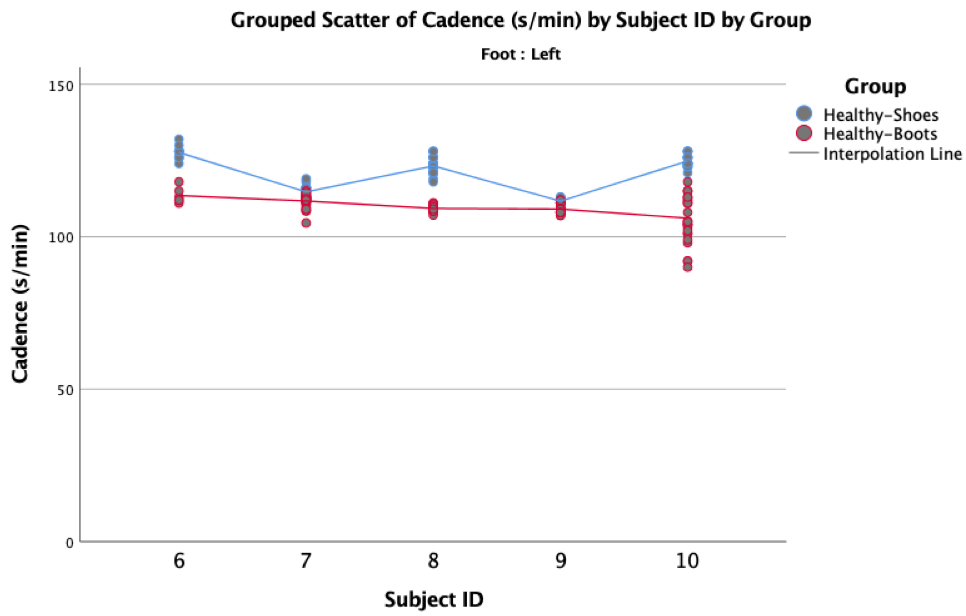

Grouped Scatter of Diff. FB (L–R) by [9] Left or right leg by [8] Injury location
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole
2.00
1.00
.00
-1.00
Diff. FB (L–R)
None
Left
Right
Both
[9] Left or right leg

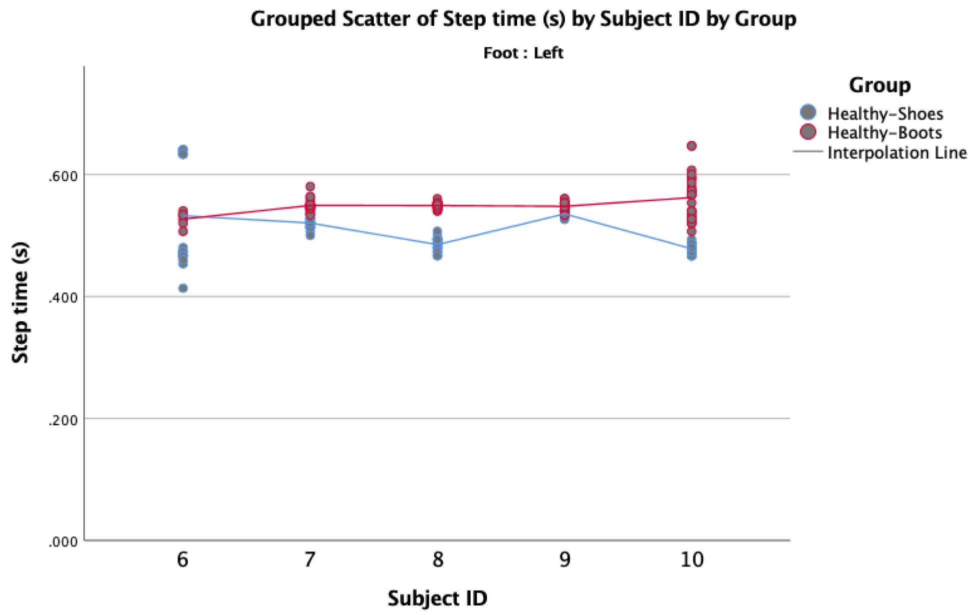

Grouped Scatter of Diff. Peak time (L–R) by [9] Left or right leg by [8] Injury location
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole
.08
.06
.04
.02
.00
-.02
Diff. Peak time (L–R)
None
Left
Right
Both
[9] Left or right leg

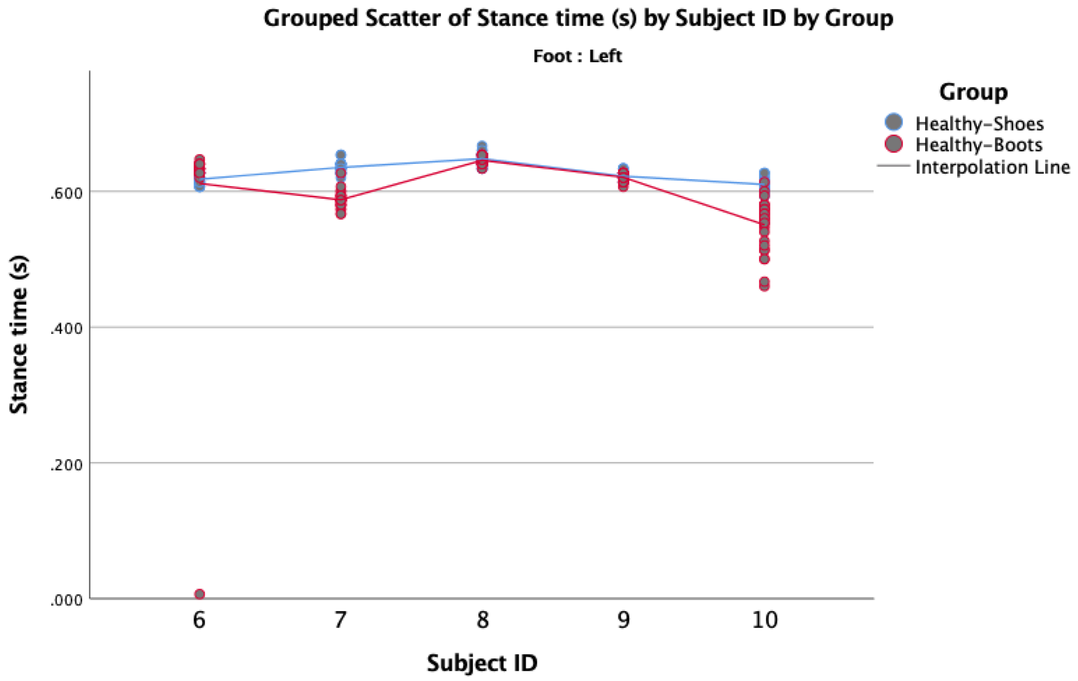

Grouped Scatter of Diff. Stance time (L-R) by [9] Left or right leg by [8] Injury location
Diff. Stance time (L-R)
.04
.02
.00
-.02
-.04
-.06
None
Left
Right
Both
[9] Left or right leg
[8] Injury location
None
Foot
Toe
Ankle
Shin
Calf
Knee
Upper leg
Lower leg whole

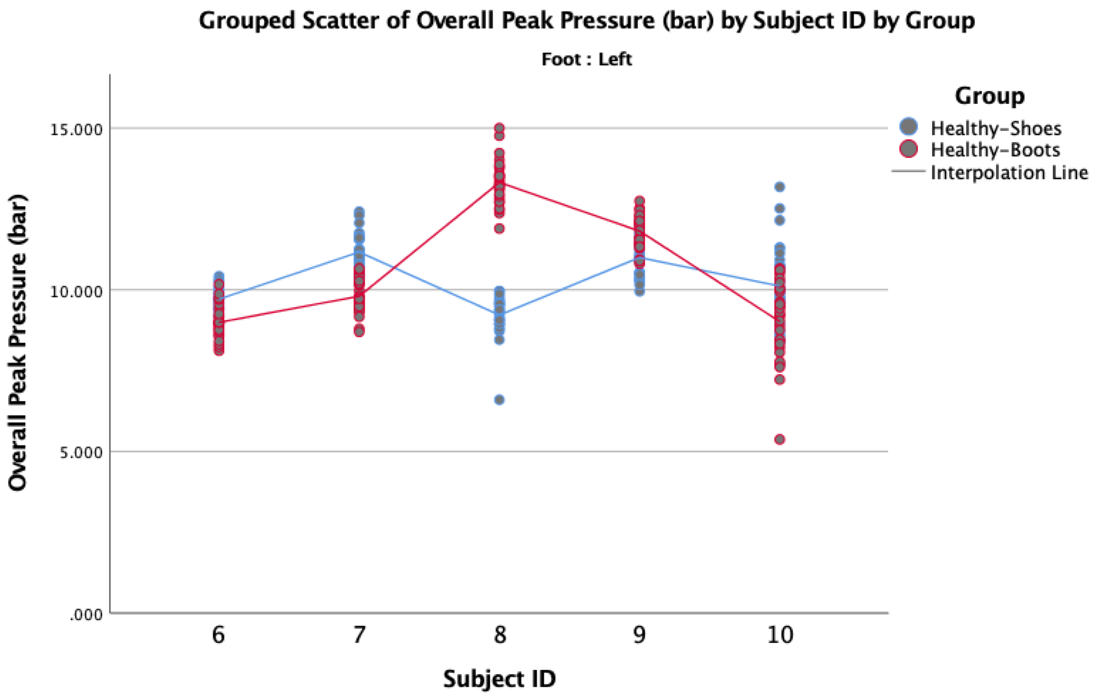
3. Study 3. Running shoes vs Army boots

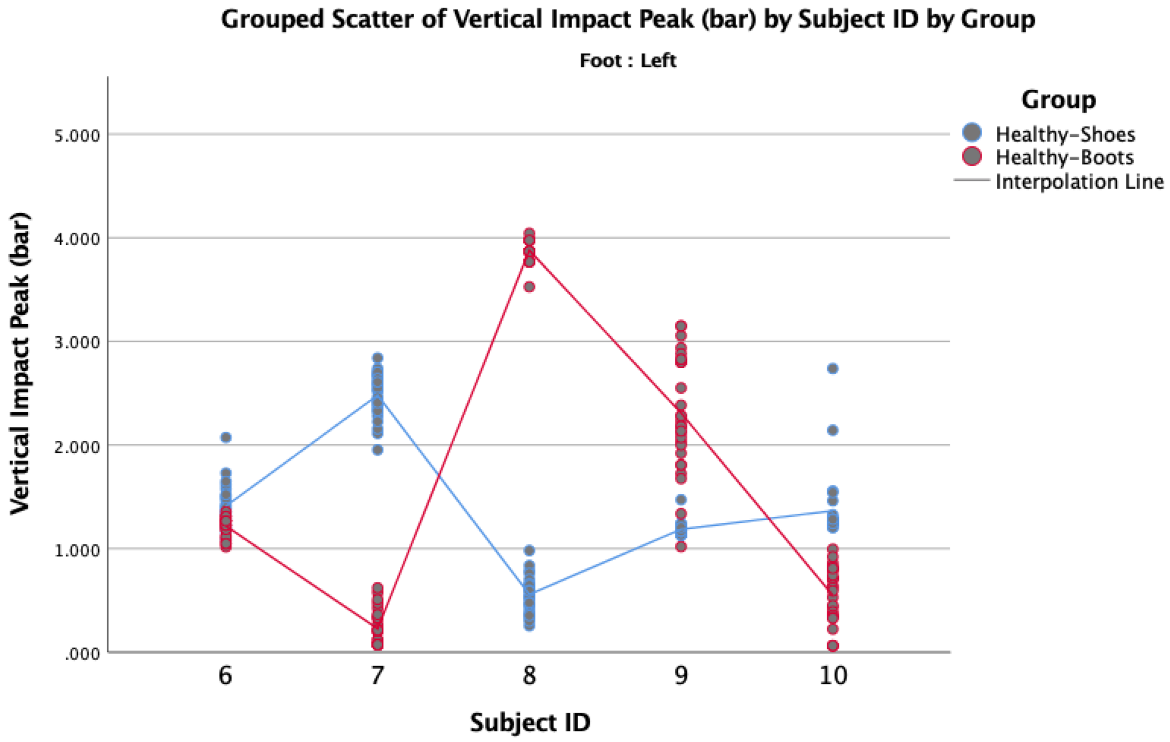
3.1 Scatter plots

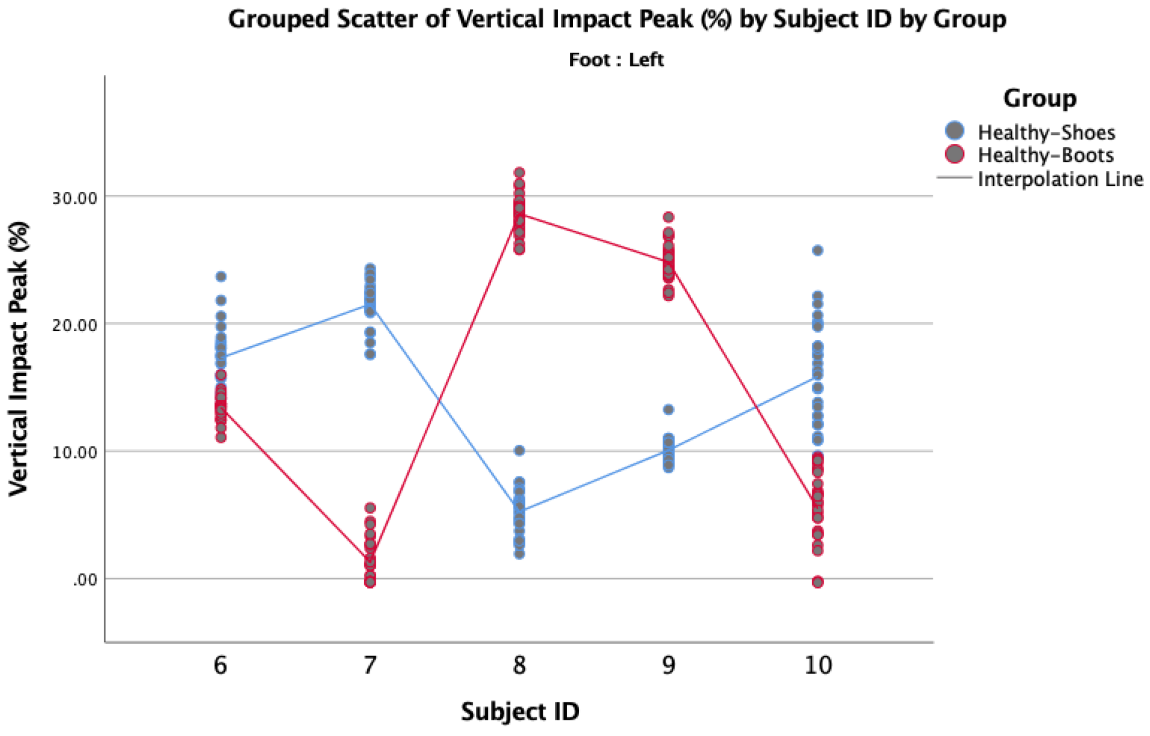


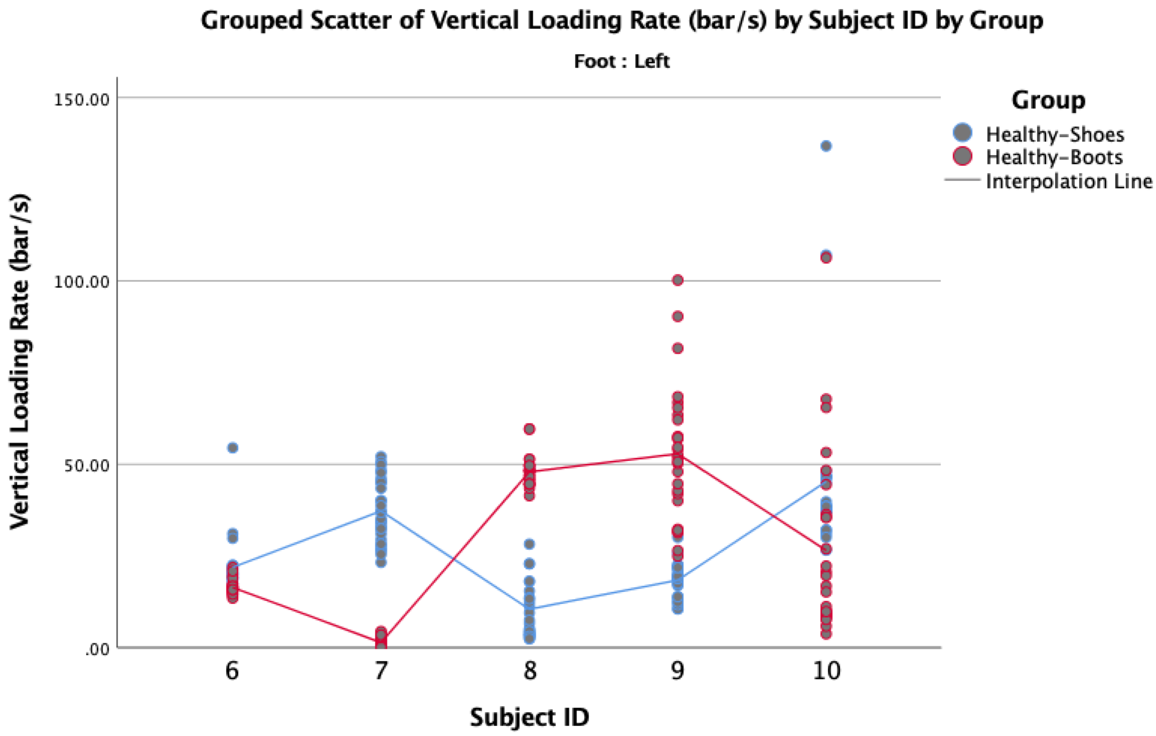



Grouped Scatter of Stance time (s) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Stance time (s)
.000
.200
.400
.600
6
7
8
9
10
Subject ID

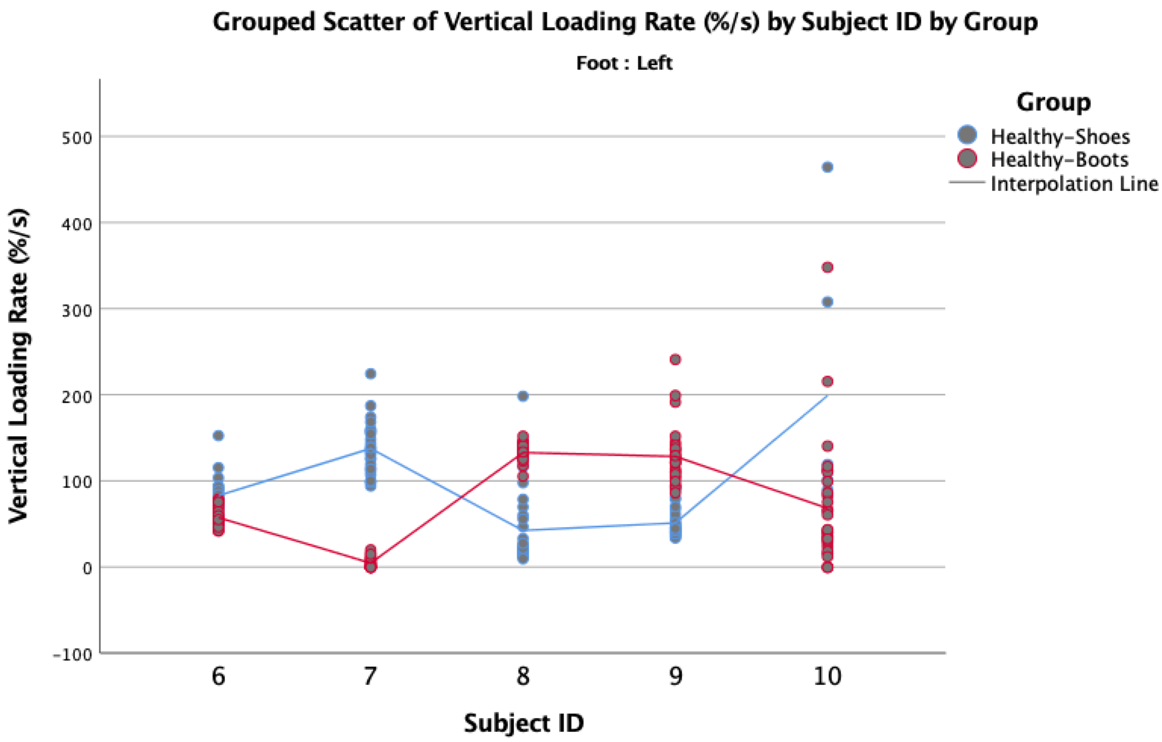

Grouped Scatter of Overall Peak Pressure (bar) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Overall Peak Pressure (bar)
.000
5.000
10.000
15.000
6
7
8
9
10
Subject ID


Grouped Scatter of Vertical Impact Peak (bar) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Vertical Impact Peak (bar)
5.000
4.000
3.000
2.000
1.000
.000
6
7
8
9
10
Subject ID

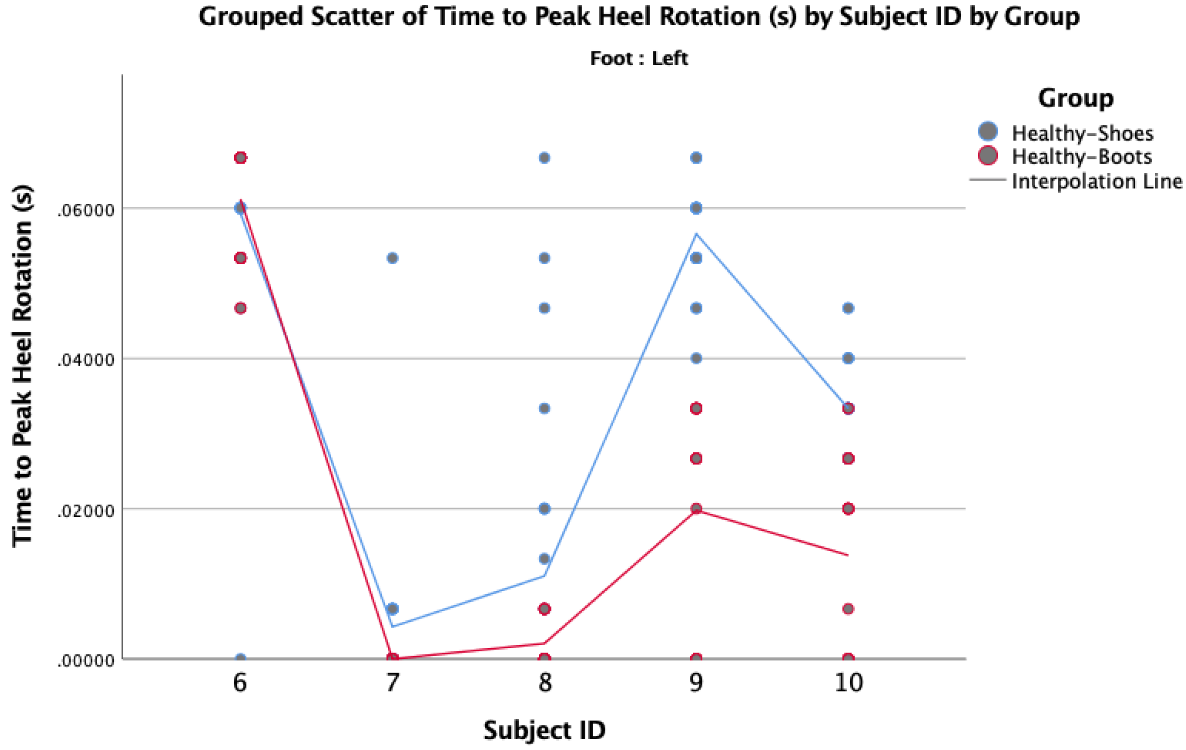

Grouped Scatter of Vertical Impact Peak (%) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Vertical Impact Peak (%)
30.00
20.00
10.00
.00
6
7
8
9
10
Subject ID

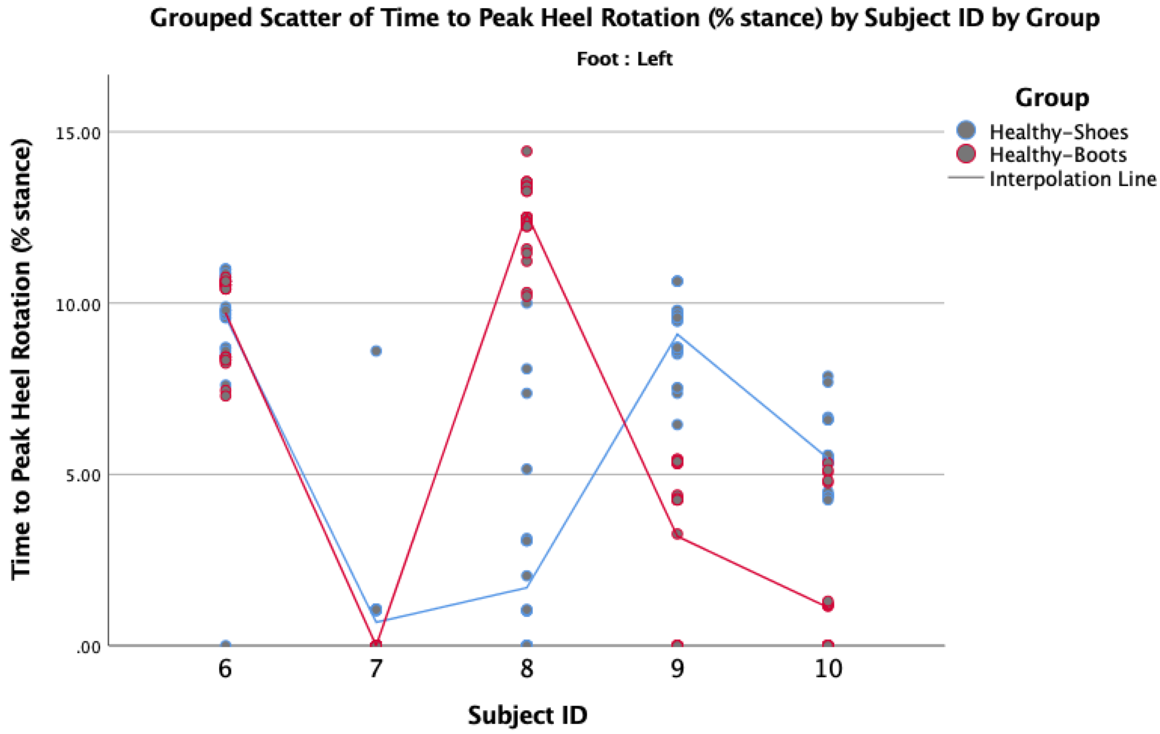


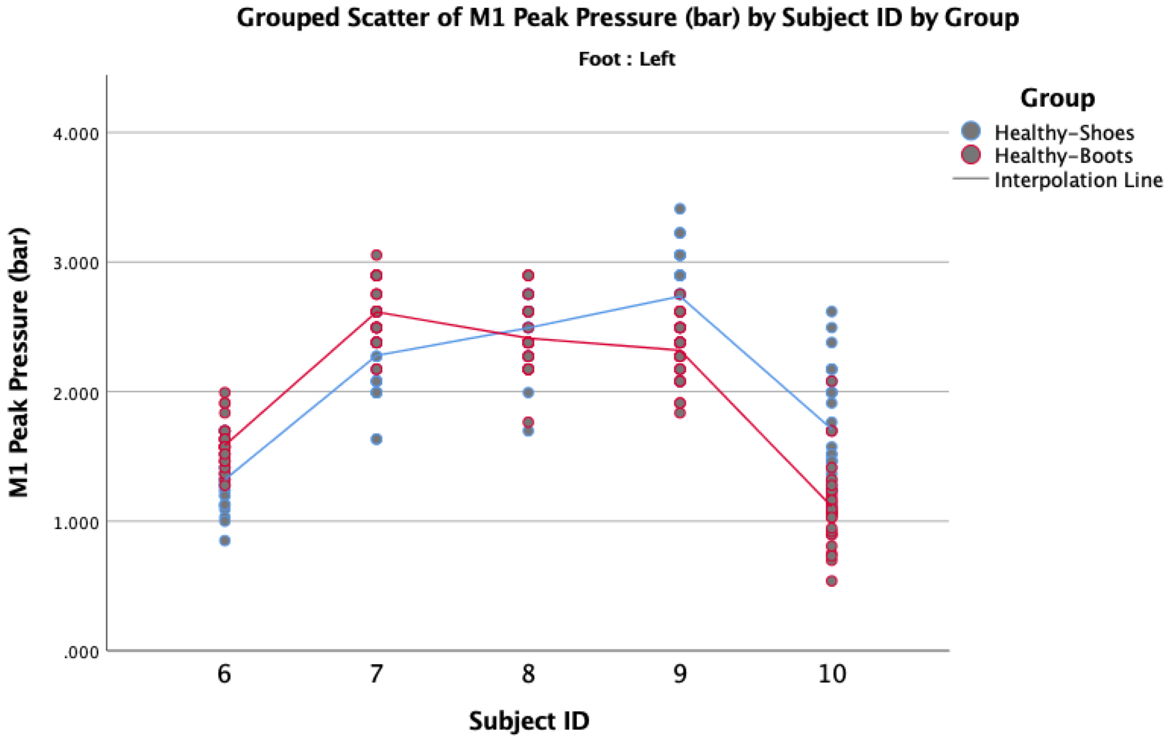
Grouped Scatter of Vertical Loading Rate (bar/s) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Vertical Loading Rate (bar/s)
150.00
100.00
50.00
.00
6
7
8
9
10
Subject ID

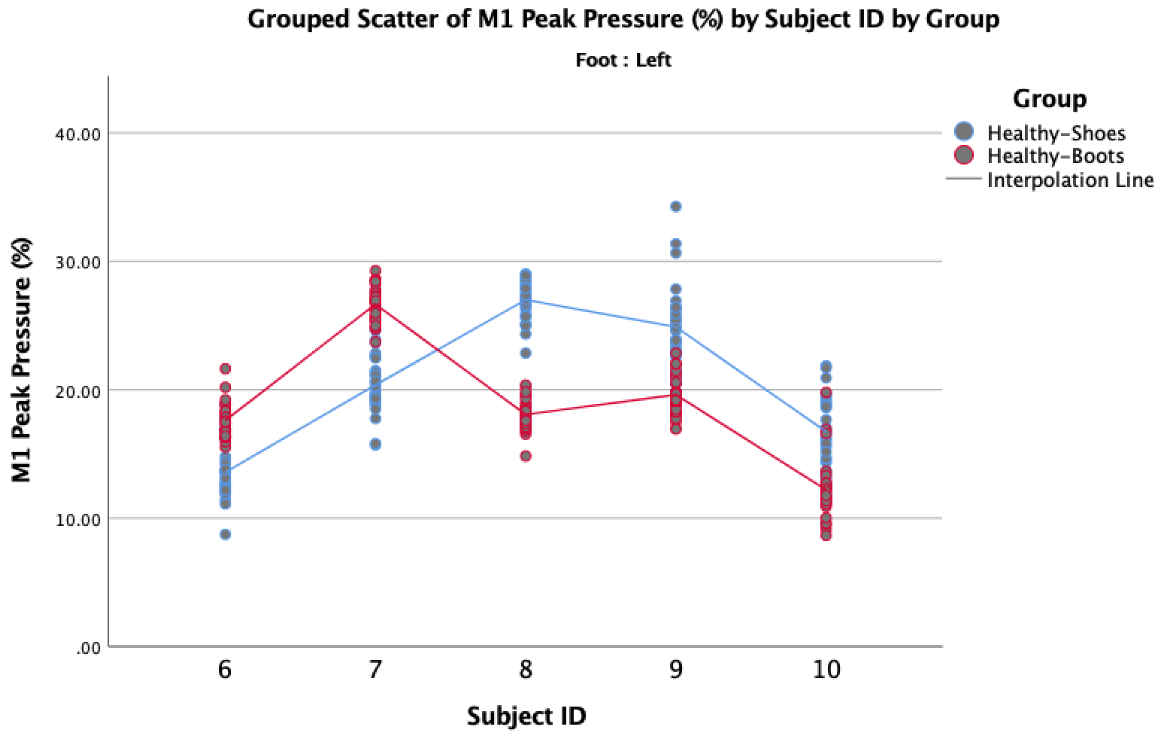


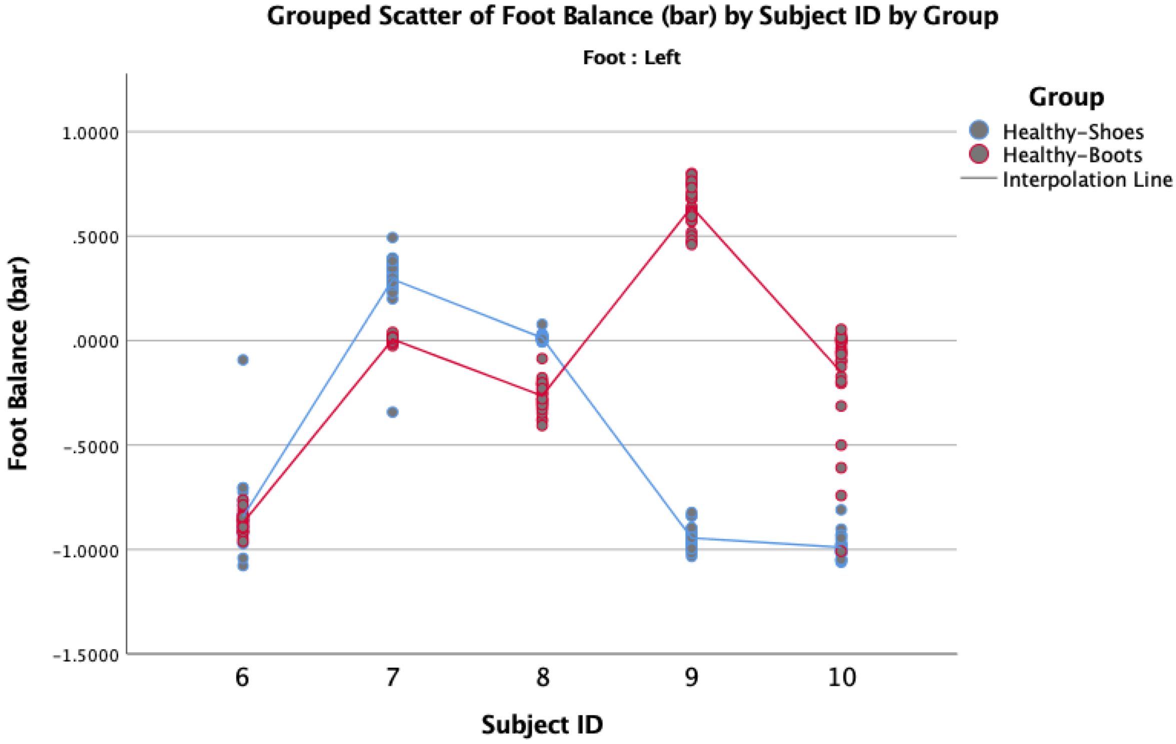
Grouped Scatter of Vertical Loading Rate (%/s) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Vertical Loading Rate (%/s)
500
400
300
200
100
0
-100
6
7
8
9
10
Subject ID


Grouped Scatter of Time to Peak Heel Rotation (s) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Time to Peak Heel Rotation (s)
.06000
.04000
.02000
.00000
6
7
8
9
10
Subject ID


Grouped Scatter of Time to Peak Heel Rotation (% stance) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Time to Peak Heel Rotation (% stance)
15.00
10.00
5.00
.00
6
7
8
9
10
Subject ID


Grouped Scatter of M1 Peak Pressure (bar) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
M1 Peak Pressure (bar)
4.000
3.000
2.000
1.000
.000
6
7
8
9
10
Subject ID


Grouped Scatter of M1 Peak Pressure (%) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
M1 Peak Pressure (%)
40.00
30.00
20.00
10.00
.00
6
7
8
9
10
Subject ID


Grouped Scatter of Foot Balance (bar) by Subject ID by Group
Foot : Left
Group
Healthy-Shoes
Healthy-Boots
Interpolation Line
Foot Balance (bar)
1.0000
.5000
.0000
-.5000
-1.0000
-1.5000
6
7
8
9
10
Subject ID

3.2 ANOVA

Descriptives[a]

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Cadence (s/min)	Healthy-Shoes	160	121.61	7.137	.564	120.50	122.73	109	138
	Healthy-Boots	121	109.23	4.425	.402	108.44	110.03	90	118
	Total	281	116.28	8.661	.517	115.27	117.30	90	138
Step time (s)	Healthy-Shoes	172	.50165	.045617	.003478	.49478	.50851	.414	.640
	Healthy-Boots	120	.55080	.020265	.001850	.54714	.55447	.507	.647
	Total	292	.52185	.044472	.002603	.51673	.52697	.414	.647
Stride time (s)	Healthy-Shoes	172	1.02508	.037692	.002874	1.01941	1.03075	.907	1.094
	Healthy-Boots	143	1.04248	.110902	.009274	1.02414	1.06081	.020	1.197
	Total	315	1.03298	.080069	.004511	1.02410	1.04185	.020	1.197
Overall Peak Pressure (bar)	Healthy-Shoes	172	10.33855	1.053364	.080318	10.18001	10.49709	6.598	13.182
	Healthy-Boots	143	10.60534	1.864451	.155913	10.29713	10.91355	5.371	14.998
	Total	315	10.45966	1.481212	.083457	10.29546	10.62387	5.371	14.998
Vertical Impact Peak (bar)	Healthy-Shoes	172	1.33162	.611111	.046597	1.23964	1.42359	.254	2.840
	Healthy-Boots	143	1.64902	1.367662	.114370	1.42293	1.87510	.064	4.043
	Total	315	1.47571	1.036497	.058400	1.36080	1.59061	.064	4.043
Vertical Impact Peak (%)	Healthy-Shoes	172	13.0557	5.99350	.45700	12.1536	13.9578	1.94	25.73
	Healthy-Boots	143	14.8265	10.79731	.90292	13.0416	16.6114	-.32	31.83
	Total	315	13.8596	8.54776	.48161	12.9120	14.8072	-.32	31.83
Vertical Loading Rate (bar/s)	Healthy-Shoes	169	24.5345	16.58504	1.27577	22.0159	27.0531	2.41	136.79
	Healthy-Boots	140	29.1709	23.62552	1.99672	25.2230	33.1188	.15	106.28
	Total	309	26.6351	20.18113	1.14806	24.3761	28.8942	.15	136.79
Vertical Loading Rate (% /s)	Healthy-Shoes	149	77.87	57.545	4.714	68.56	87.19	10	464
	Healthy-Boots	143	78.91	60.020	5.019	68.98	88.83	0	348
	Total	292	78.38	58.671	3.433	71.62	85.14	0	464
Time to Peak Heel Rotation (s)	Healthy-Shoes	172	.0363360	.02452852	.00187028	.0326442	.0400278	.00000	.06670
	Healthy-Boots	144	.0195005	.02414689	.00201224	.0155229	.0234781	.00000	.06670
	Total	316	.0286641	.02572607	.00144720	.0258167	.0315115	.00000	.06670
M1 Peak Pressure (bar)	Healthy-Shoes	172	1.98462	.632894	.048258	1.88936	2.07988	.849	3.411
	Healthy-Boots	143	2.00786	.620078	.051854	1.90536	2.11037	.538	3.054
	Total	315	1.99517	.626220	.035284	1.92575	2.06459	.538	3.411
M1 Peak Pressure (%)	Healthy-Shoes	172	19.1999	5.93752	.45273	18.3063	20.0936	8.73	34.27
	Healthy-Boots	143	18.7797	4.91239	.41080	17.9677	19.5918	8.65	29.27
	Total	315	19.0092	5.49143	.30941	18.4004	19.6179	8.65	34.27
Foot Balance (bar)	Healthy-Shoes	172	-.556763	.5174612	.0394560	-.634646	-.478879	-1.0778	.4929
	Healthy-Boots	143	-.124323	.5029810	.0420614	-.207470	-.041175	-1.0091	.8003
	Total	315	-.360449	.5538354	.0312051	-.421846	-.299051	-1.0778	.8003
Peak Time (s)	Healthy-Shoes	169	.06907	.038663	.002974	.06320	.07494	.013	.213
	Healthy-Boots	132	.07074	.044326	.003858	.06311	.07837	.000	.207
	Total	301	.06980	.041180	.002374	.06513	.07447	.000	.213
Stance time (s)	Healthy-Shoes	172	.61756	.025351	.001933	.61374	.62138	.547	.667
	Healthy-Boots	144	.60345	.063379	.005282	.59301	.61389	.007	.654
	Total	316	.61113	.047138	.002652	.60591	.61635	.007	.667
Time to Peak Heel Rotation (% stance)	Healthy-Shoes	172	5.9816	4.05877	.30948	5.3707	6.5925	.00	12.05
	Healthy-Boots	143	5.3317	5.20335	.43513	4.4716	6.1919	.00	14.43
	Total	315	5.6866	4.61740	.26016	5.1747	6.1984	.00	14.43

a. Foot = Left

ANOVA[a]

		Sum of Squares	df	Mean Square	F	Sig.
Cadence (s/min)	Between Groups	10555.952	1	10555.952	281.830	.000
	Within Groups	10449.947	279	37.455		
	Total	21005.899	280			
Step time (s)	Between Groups	.171	1	.171	122.391	.000
	Within Groups	.405	290	.001		
	Total	.576	291			
Stride time (s)	Between Groups	.024	1	.024	3.718	.055
	Within Groups	1.989	313	.006		
	Total	2.013	314			
Overall Peak Pressure (bar)	Between Groups	5.558	1	5.558	2.546	.112
	Within Groups	683.355	313	2.183		
	Total	688.913	314			
Vertical Impact Peak (bar)	Between Groups	7.866	1	7.866	7.473	.007
	Within Groups	329.472	313	1.053		
	Total	337.338	314			
Vertical Impact Peak (%)	Between Groups	244.841	1	244.841	3.376	.067
	Within Groups	22697.319	313	72.515		
	Total	22942.160	314			
Vertical Loading Rate (bar/s)	Between Groups	1645.978	1	1645.978	4.082	.044
	Within Groups	123795.678	307	403.243		
	Total	125441.656	308			
Vertical Loading Rate (% /s)	Between Groups	78.081	1	78.081	.023	.881
	Within Groups	1001636.81	290	3453.920		
	Total	1001714.89	291			
Time to Peak Heel Rotation (s)	Between Groups	.022	1	.022	37.451	.000
	Within Groups	.186	314	.001		
	Total	.208	315			
M1 Peak Pressure (bar)	Between Groups	.042	1	.042	.107	.743
	Within Groups	123.093	313	.393		
	Total	123.136	314			
M1 Peak Pressure (%)	Between Groups	13.786	1	13.786	.456	.500
	Within Groups	9455.148	313	30.208		
	Total	9468.934	314			
Foot Balance (bar)	Between Groups	14.602	1	14.602	55.932	.000
	Within Groups	81.713	313	.261		
	Total	96.314	314			
Peak Time (s)	Between Groups	.000	1	.000	.122	.727
	Within Groups	.509	299	.002		
	Total	.509	300			
Stance time (s)	Between Groups	.016	1	.016	7.163	.008
	Within Groups	.684	314	.002		
	Total	.700	315			
Time to Peak Heel Rotation (% stance)	Between Groups	32.974	1	32.974	1.549	.214
	Within Groups	6661.624	313	21.283		
	Total	6694.598	314			

a. Foot = Left

3.3 Effect sizes

Measures of Association[a]

	Eta	Eta Squared
Cadence (s/min) * Group	.709	.503
Step time (s) * Group	.545	.297
Stride time (s) * Group	.108	.012
Overall Peak Pressure (bar) * Group	.090	.008
Vertical Impact Peak (bar) * Group	.153	.023
Vertical Impact Peak (%) * Group	.103	.011
Vertical Loading Rate (bar/s) * Group	.115	.013
Vertical Loading Rate (% /s) * Group	.009	.000
Time to Peak Heel Rotation (s) * Group	.326	.107
Time to Peak Heel Rotation (% stance) * Group	.070	.005
M1 Peak Pressure (bar) * Group	.019	.000
M1 Peak Pressure (%) * Group	.038	.001
Foot Balance (bar) * Group	.389	.152
Peak Time (s) * Group	.020	.000
Stance time (s) * Group	.149	.022

a. Foot = Left

Appendix 6.

LIST OF REQUIREMENTS & WISHES

Requirements	Sub-requirements		InnoGait rating
1. Performance			
The product can measure one or more biomechanical parameters linked to OLLI injury prediction (see literature conclusion)			
The software can detect gait parameters (using heel strike, foot-flat, toe off, contralateral toe off, heel rise and contralateral heel strike)			
2. Electronics			
Can measure peak pressures up to 300 KPa			
Can be used for at least 10 hours (long march) without charging			
Battery can be charged in bulk			
	The battery is removable from the insole		
	The batteries are charged via a (wireless) docking station		
	A single docking station holds more than 10 pairs of batteries		
Collective data from groups of subjects (patients) is visible to authorized users			
	Data transfer is wireless		
	Application offers data-sharing services		
	Authorization is complient with personal and medical regulations		
3. Data			
Data is presented in a way that is usable for a therapist			
	Data is numerical, segment specific and shows loading rate		
Data is analysed and constantly updated to improve quality of injury prediction according to injury prevalence (machine-learning)			

4. Use			
The product does not need to be calibrated by the direct user (recruit)			
	The product is calibrated right after fabrication inside the shoe		
	The electronics do not change in throughput values throughout its lifecycle		
The product is easy to clean			
	Surface finish and electronics allow for either rinsing or washing machine		
	Electronics can be removed from the fabrics		
5. Embodiment			
The product is intrusive			
	Insole is not (tactilly) sensible under the foot		
	External electronics do not increase perceived weight to the army boot		
	External electronics do not wobble when moving		
The product is resistant to heavy use			
	Electronic circuit is protected to water damage		
	Can resist (burst) pressure of up to 300 KPa without failing or need for recalibration		
	Donning and doffing the insoles in the shoes does not cause high tearing-stresses		
	Product can be used at least 10 cycles without failure (appr. 2 cycles per recruit)		
6. Cost			
Use of the product should not cost money to the individual users, other than the buyer (Defense)			
Retail price is cheaper than 546 euro per pair			
There is value for an investor to cover the research period before product launch			
7. Viability			
The product targets the domain of accuracy combined with user-centered design			

The product is a multi-diagnostic tool and targets both businesses and consumers		
The product has a potential to enter other target markets		
8. Sustainability		
The product's life-span is at least two years (used only during basic training)		
Individual electronics can be disassembled and replaced for repair		
Insole itself can be replaced		
Software can be updated without hardware update		
Old products are collected for recycling or responsible End-of-Life		

Wishes	Category				InnoGait rating
	Electronics	Software	Embodiment	Service system	
The product can detect multiple types of intrinsic risk factors					
The product collects relevant data for research and future applications					
The product can calculate the weight of packaging carried (on the back)					
The product can calculate energy consumption					
The product can recognize different terrain types					
The product can export data with which an insole manufacturer can produce customized insoles					
The product reports individual results back to the soldier and general statistics to the entire unit					
The service-system digitally connects all stakeholders according to their interaction type					
Predictive accuracy of the product is higher than a system using only inertial sensors					

Predictive accuracy of the product is not significantly lower than the predictive accuracy of a force plate						
The product collects success-statistics to increase trustworthyness						
The product is available for both business and consumer market						
Data is processed and presented in a way that is usable for the different stakeholders:						
	Interaction with a sports instructor is: Simple, clear, statistical, mobile and has personal progress monitoring					
	Interaction with a soldier is: comforting, taking seriously, offering a hand, respected					
	Interaction with a sergeant is: color-coded, visual, efficient, clear					
	Interaction with a physiotherapist is: constructive, physical, detailed, personal, informative					
	Interaction with a insole manufacturer is: numeric, automated, detailed, anonymous					
The product acts on stakeholder's "worries":						
	The product helps Defense to plan operations using soldier fitness data					
	The product supports communication efficiency between soldiers, sergeants, corporals, physiotherapists, sports instructors and insole manufacturers					
	The product provides feedback to individual soldiers about their fitness					
	The product has a live-feedback function to alarm supervisors or soldiers for risky situations					
The product uses the intelligence capabilities of computers to improve functionality						

The army boot does not need to be adjusted to fit the product					
Insole is compatible with other (orthopaedic) insoles					

Appendix 7.

INJURY ASSESSMENT DESIGN

According to the paragraph 6.1 in the Literature study (Appendix 3), the three injury types in theory could be measured with twelve different parameters (see Table 2, originated from Appendix 3). Some parameters measure multiple injury types. Some parameters are affected by other parameters (dependent parameters), which means that exclusion of one of them might be possible to predict an injury. Table A7.1 shows which type of measurement tool is able to measure the different parameters and which threshold could be assumed as high risk, according to different sources of literature. These measurement tools are narrowed down to pressure sensing and IMU sensing according to results of paragraph 6.2.

Table A7.1 - Risk parameters and how to measure them

Parameter		FAI %	**PTS** *g* ; m.s/2	**MP** °	iCoP *mm*	Cad s/m	**VIP** *BW*; KPa ; N.cm^{-2}	VLR BW.s^{-1}	**FB** *KPa* ; N.cm^{-2}	TPHR %	**KP** ° ; mm	**CE** ° ; kPa
Dependent parameter		SA / TA	SL	TFM / FB		VIP	SL	VIP / C / MP	MP / KP / FP	MP / iCoP	SA / FAH TA / iCoP	FAH / TA / SA
Injury type	MTSS											
	TSF											
	ITBS											
Risk-threshold value		<21 / >28 - high <15 / >34 - very high	5 - mod 10 - high 15 - Very high	50 - mod 54 - high	20 - mod 25 - high	<170 - mod <160 - high <150 - very high	1.70 - mod 1.80 - high 1.85 - very high	80 - mod 90 - high 95 - very high	-14 - mod -18 - high -22 - very high	25,5 - mod 28,5 - high	3.9	9.7
Measurement	Pressure sensing											
	IMU sensing											

Table A7.1: parameters (Foot Arch Index = FAI; Peak Tibial Shock = PTS; Midfoot Pronation = MP; initial Centre of Pressure = iCoP; Cadence = C; Vertical Impact Peak = VIP; Vertical Loading Rate = VLR; Foot Balance = FB; Time to Peak Heel rotation = TPHR; Knee pronation = KP; Calcaneal eversion = CE; Tibial Free Moment = TFM) and injury types (Medial Tibial Band Syndrome = MTSS; Tibial Stress Fracture = TSF; Iliotibial Band syndrome = ITBS)

Table A7.1 can be used for an assessment study and is therefore transformed into an assessment sheet (Figure A7.1). Using the protocol as illustrated in Figure A7.2, parameters will be obtained and can be filled into the assessment sheet to provide a diagnosis. A simpler version of this sheet is validated in the research from Section 2.1 of the main report and Appendix 5.

Risk value	Parameter						
	Cadence	Foot Arch Index	Peak Tibial Shock	Midfoot Pronation	Time t.p. Heel Rotati	Vertical Loading Ra	Vertical Impact Pea
	(s/m)	(%)	(g)	(kPa)	(% of stance)	(BW / s-1)	(BW)
Healthy (0)	>170	21-28	<5	<60	<25,5	<80	<1,7
Moderate risk (1)	<170	<21 / >28	>5	>60	>25,5	>80	>1,7
High risk (50)	<160	<15 / >34	>10	>100	>28,5	>90	>1,8
Very high risk (100)	<150	(<10 / >40)	>15	(>130)	(>31,5)	>95	>1,85
Risk score (0-100)	20-(C-150)/20*100	IF<21:11-(FAI-10)/11*1	(PTS-5)/10*100	(MP-60)/70*100	(TPHR-25,5)/6*100	(VLR-80)/15*100	(VIP-1,7)/0,15*100
Risk score MTSS	+	+	+	+	+	+	+
Risk score TSF	+		+			+	+
Risk score ITBS	+		+	+			

Foot Balance	Knee Pronation	Calcaneal Eversion		initial Centre of Pressure (mm)			Repetition factor			Final Risk score
(kPa)	(deg)	(deg)	(kPa)							
<14	<3,9	<9,7	<178	<21			<10.000		Healthy	<25
>14	>3,9	>9,7	>178	>21			>10.000		Moderate risk	>25
>18	(>4,5)		>222	>25			>20.000		High risk	>50
>22	(>5)		>250	>28			>30.000		Very high risk	>75
(FB-14)/8*100	(KP-3,9)/1,1*100		(CE-178)/72	(iCoP-21)/7*100			1+(R-10000)/50000			
+				+	/8	>	x	>	Risk score MTSS	
+	+	+		+	/7	>	x	>	Risk score TSF	
	+			+	/4	>	x	>	Risk score ITBS	

Figure A7.1: Assessment sheet

Figure A7.2: Software development steps

Risk value	**Parameter**							
	Cad	***TPHR***	***VLR***	***VIP***	***FB***		***M1***	
	(s/m)	***(% stance)***	***(BW / s-1)***	***(BW)***	***(bar)***	***(mm)***	***(bar)***	
Healthy (0)	>170	<25,5	<80	<1,7	<0.14	<14	<0.60	
Moderate risk (1)	<170	>25,5	>80	>1,7	>0.14	>14	>0.60	
High risk (50)	<160	>28,5	>90	>1,8	>0.18	>18	>1.00	
Very high risk (100)	<150	*(>31,5)*	>95	>1,85	>0.22	>22	(>1.30)	
Risk score (0-100)	20-(C-150)/20*100	(TPHR-25,5)/6*100	(VLR-80)/15*100	(VIP-1,7)/0,15*100	(FB-14)/8*100	(FB-14)/8*100	(MP-60)/70*100	
Risk score MTSS	+	+	+	+	+	+	+	/8
Risk score TSF	+		+	+	+	+		/7
Risk score ITBS	+						+	/4

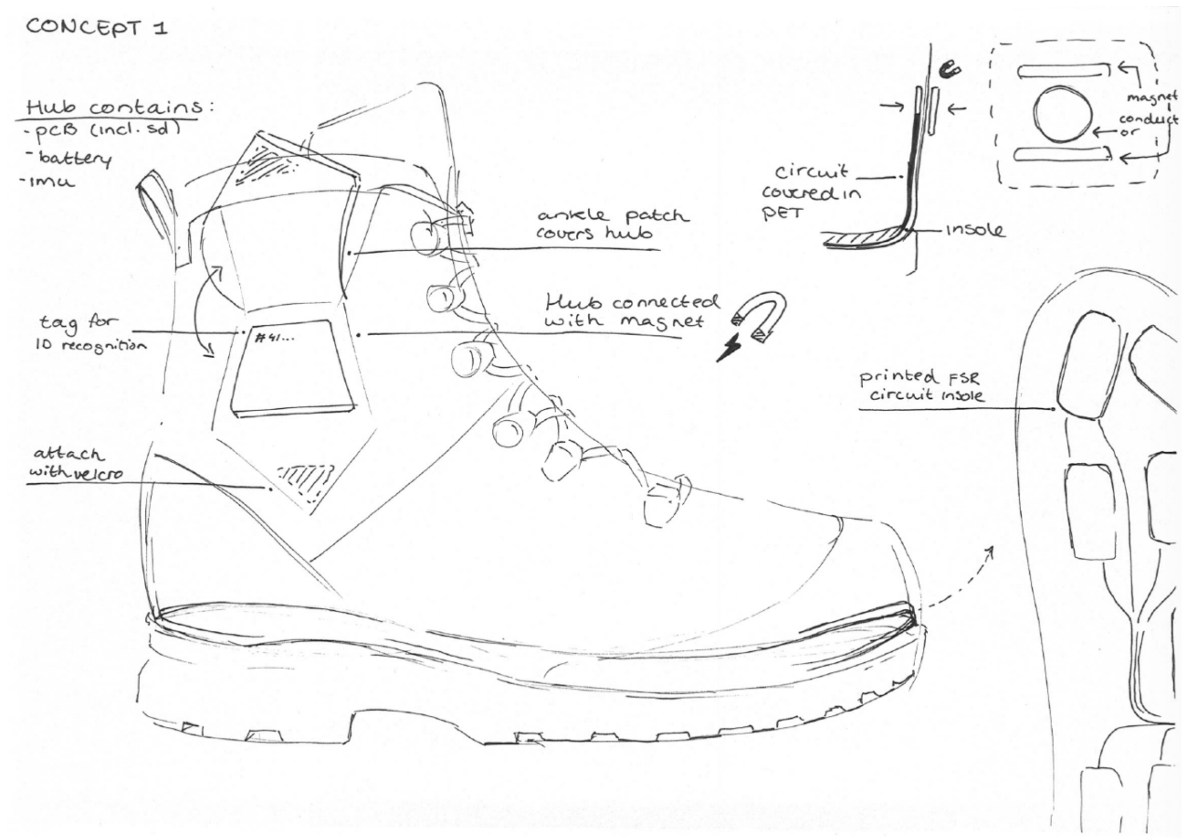
	Repetition factor			**Final Risk score**
	<10.000		*Healthy*	<25
	>10.000		*Moderate risk*	>25
	>20.000		*High risk*	>50
	>30.000		*Very high risk*	>75
	1+(R-10000)/50000			
>	x	>	Risk score MTSS	
>	x	>	Risk score TSF	
>	x	>	Risk score ITBS	

Figure A7.3: Assessment sheet technology-driven studies

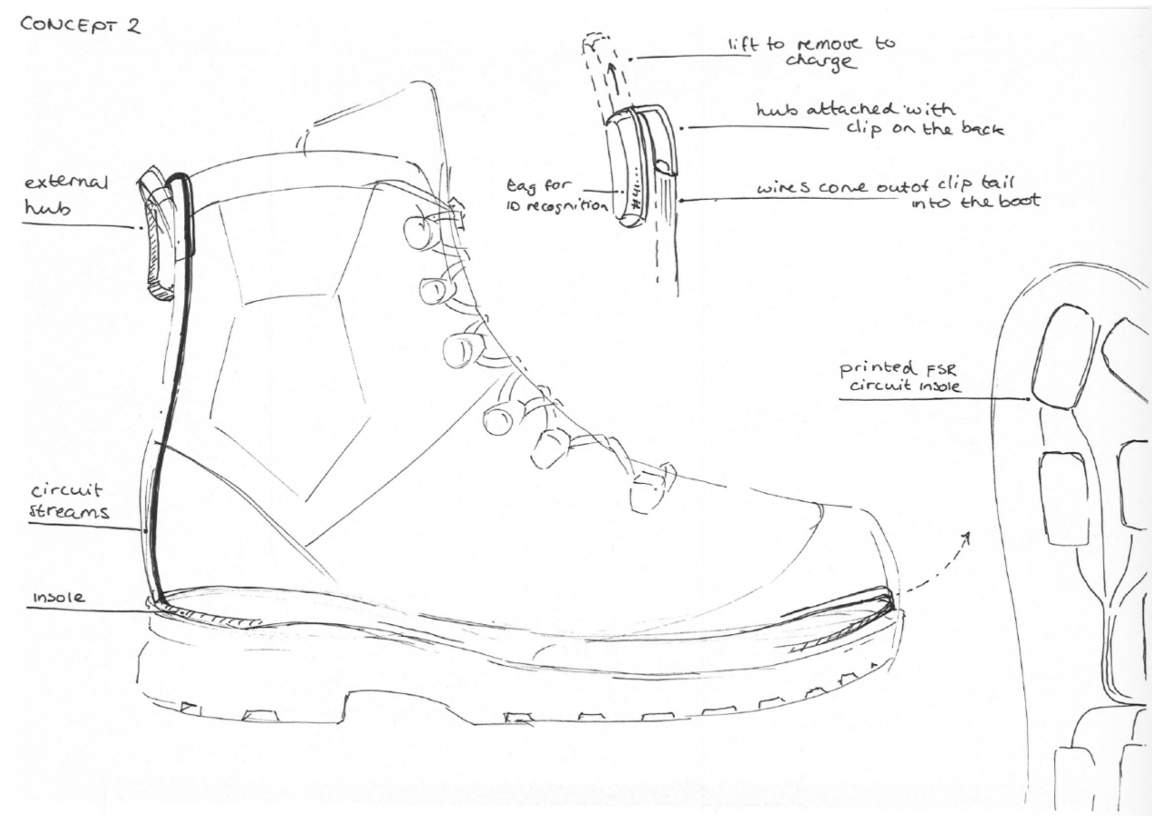
Appendix 8.

DESIGN SKETCHES

Figure A8.1 - Brainstorm sketches

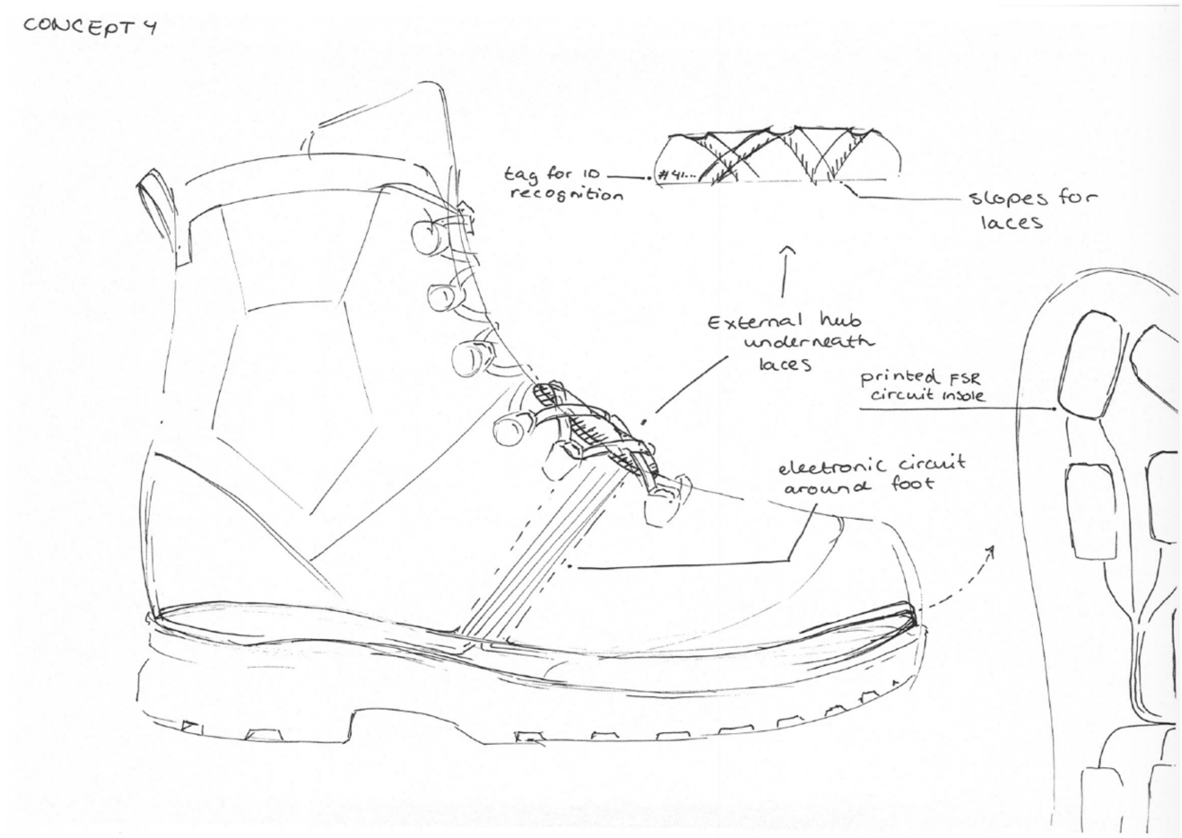

CONCEPT 1
Hub contains:
- PCB (incl. sd)
- battery
- imu
ankle patch covers hub
Hub connected with magnet
tag for ID recognition
attach with velcro
circuit coverd in PET
insole
magnet
conductor
printed FSR circuit insole

a


CONCEPT 2
lift to remove to charge
hub attached with clip on the back
tag for ID recognition
wires come outof clip tail into the boot
external hub
printed FSR circuit insole
circuit streams
insole

b

c



d

Figure A8.2a-d - External hub ideation

Appendix 9.

MORPHOLOGICAL MAP

Table A9.1 – Morphological map with color clustering

How to..	Most Preferred option A	B	C	D	E	Least Preferred option F	Clusters			
1 Measure most parameters?	*Intertial sensors*	*Defined FSR locations*	*Timing of gait*	*Contact area array*	*Contour lines*	*Heel rotation*	A B C	A C	B C E	D E
2 Identify the user before use?	*Manual input nr.*	*NFC tag*	*Bluetooth button*	*Assigned nr.*						
3 Charge / read data in bulk?	*Hub docking station*	*Bluetooth sync*	*Charging boot plate*							
4 Integrate parts in insole?	*Printed circuit*	*Printed FSRs*	*Sensor cut-out*	*Between layers*			A B	A B D		
5 Attach external hub on boot?	*Underneath laces*	*Clip on the back*	*Inside rubber heel*	*Clip on the side*	*Drill hole for wire*	*Magnetic*				
6 Limit amount of sensors used?	*Use sensor strips*	*Simulate with shoe constants*	*Excl. correlated parameters*	*Interpolation*	*Calculate load using known BW*	*Measure loading with IMU*	A B C D	B C E F		
7 Protect against heavy use?	*Laminated electronics*	*Strong surface material*	*Place below regulare insole*	*Hub strategically placed*	*Easy don/doff*	*High burst value electronics*	A B D E F	A C D E F	D E	
8 Design 4 repair and cleaning?	*Removable film layer*	*Printed circuit (add ink)*	*Stitches and sowing*	*Cutting lines to replace parts*	*Water repellant top layer*	*Removable electronics*	A B C E	A C E F	A B C D E	
9 Normalize data stream?	*Clustered control groups*	*Relative to BW*	*Relative to foot length/width*	*Spatiotemporal data clustering*	*Calibrate each user*		A B C D	A B C D E	C D	
10 Process 4 insole fabrication?	*Value profile mapping*	*Mean pressure map*	*Manual (app) input values*	*Parameter values (e.g. arch height)*	*Standard inner shoe shape*		A C E	B C E	C D E	
11 Reduce environmental impact?	*3D printing (no waste product)*	*In-house printing (no shipping)*	*Order-based production (no inventory)*	*Detailed data (no iterations)*	*Deliver to warehouse (less shipping)*	*Deliver to base camp (less shipping)*	A C D E	A B C D E		

Appendix 10.

ANTHROPOMETRIC STUDY

Results from the literature review determined the high potential of injury prediction based on biomechanical parameters. However, since every individual's foot is different in size and anthropometry, it is difficult to determine where the the measurements should take place for every individual to measure the same parameter. Therefore, an anthropometric study is performed with the hypothesis:

An anthropometric framework consisting of longitudinal foot length and transverse forefoot and heel axes can be standardized for each shoe size.

By analyzing the spread of anthropometric values of distance to standardized landmarks of the footprints and the locations of peak pressure, conclusions can be drawn regarding:
Different sizings for the insole, placement of sensors per size, the size of the sensors, the necessity of in-use normalisation algorithms to be able to compare results between all users

To test the hypothesis, a dataset of CAD WALK pressure values (Booth et al, 2018) is processed in Paraview and analyzed statistically in Excel and SPSS. Data from 31 individual's single stance, left foot measurements was included in the study, ranging from size 37 to 48.

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1. Method

1.1 Footprint preparation

Before measuring any parameter, the trials were processed to form a peak pressure map of all pixels involved in the stance.

1.2 Framework setup

Figure A10.1a shows an illustration of the framework, applied on an example footprint. To determine the coordinates of point A-H, the ruler tool in Paraview was used to draw a line segment from the heel to the Hallux, where this length was maximal (Figure A10.1b). Next, a line segment was drawn from medial heel to medial forefoot where this line intersects with the foot contour (Figure A10.1c). The same is done for the lateral side of the foot (Figure A10.1d).

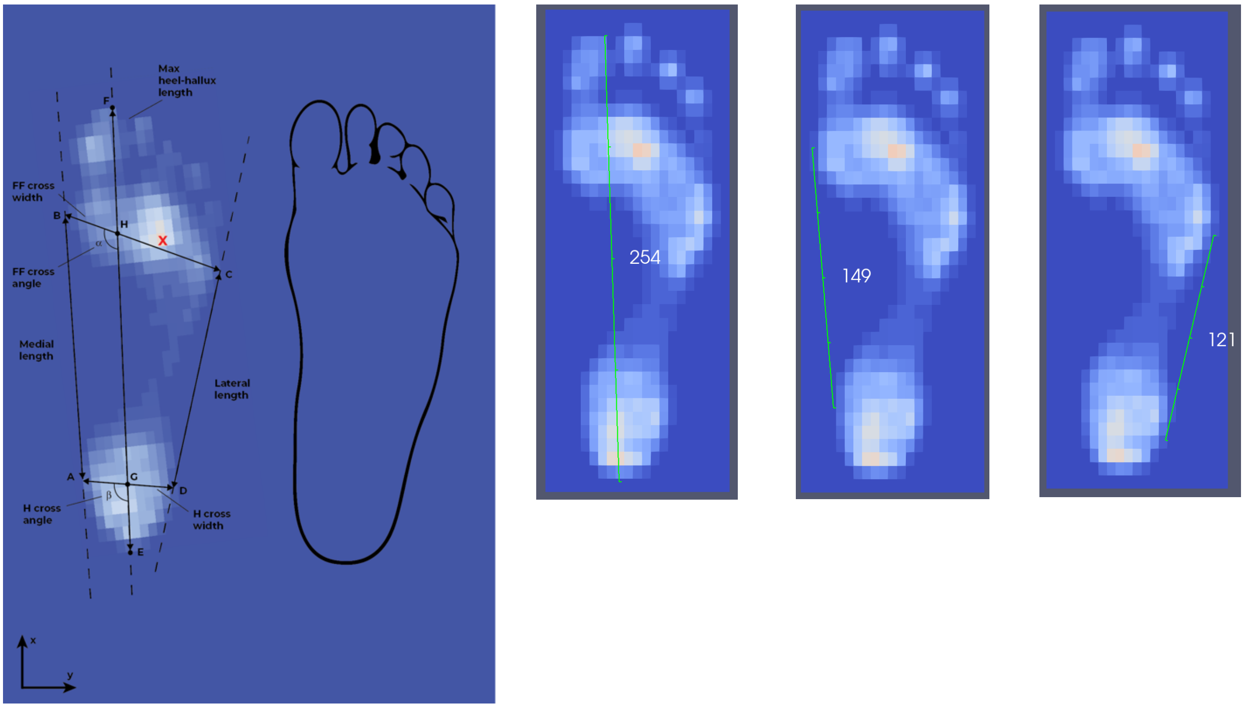


Figure A10.1: (a) Wireframe and (b) measurements of heel-hallux, (c) medial heel to forefoot and (d) lateral heel to forefoot

1.3 Peak pressure locations

Using the same ruler tool, the location of the maximum pressure value for each footprint was located in terms of x-and y coordinates.

2. Framework graphs

Using the coordinates found in Paraview, the line segments as illustrated in Figure A10.1a were calculated in Excel. To find the effect of shoe size on these segment lengths, angles and intersection locations, the values were plotted over shoe size (Figure A10.2). The compared values are:

Shoe size - heel hallux
Shoe size - crossline width (forefoot and heel)
Shoe size - heel cross intersection (medial and distal)
Shoe size - forefoot cross intersection (medial and distal)
Shoe size - crossline angles (forefoot and heel)

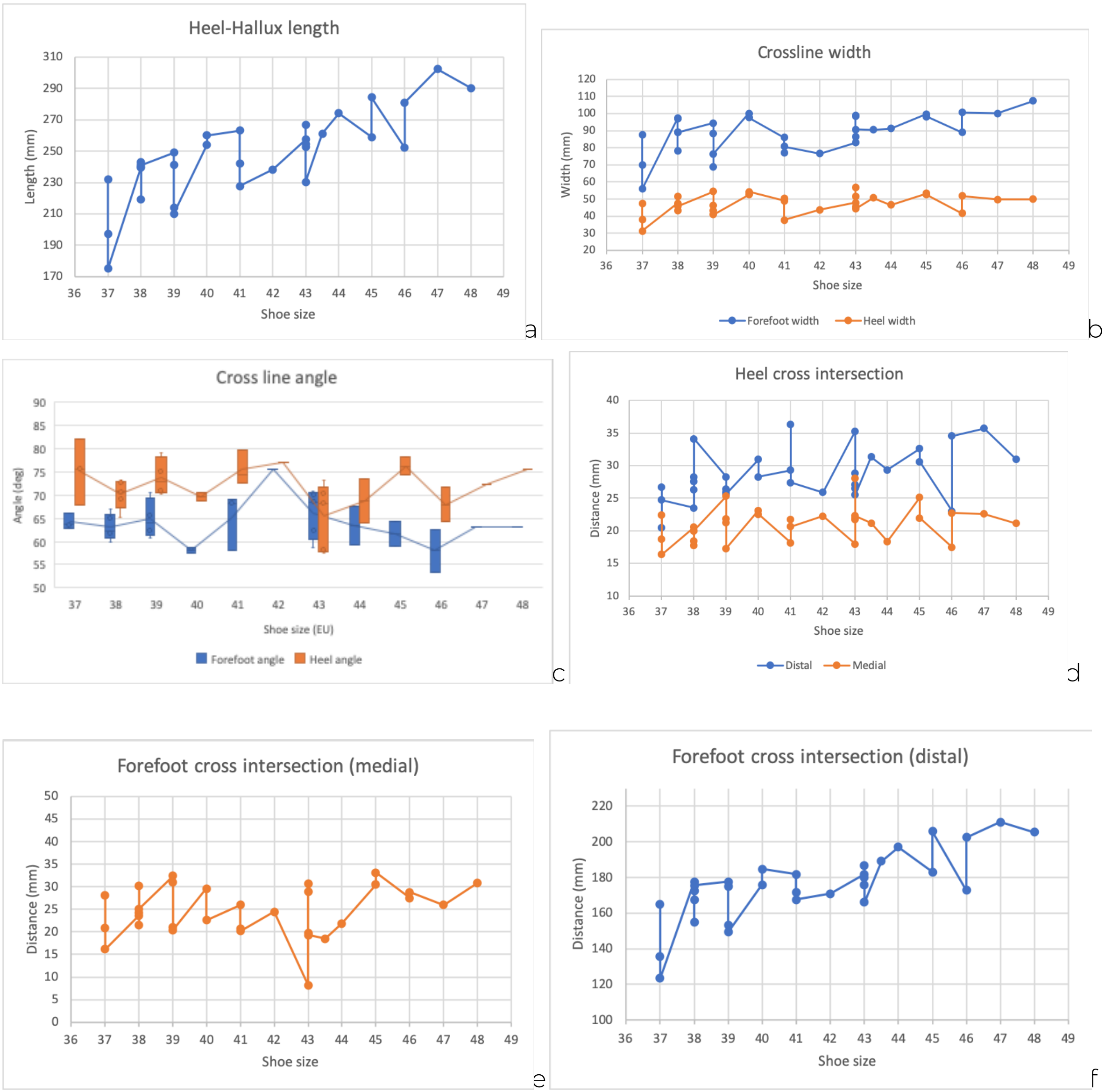


Figure A10.2: Dimension plots along shoe size

The plots of Heel-hallux length (Figure A10.2a) and the distal Forefoot cross intersection (Figure A10.2f) show a slight regression along the Shoe size axis. The other plots do not visibly show any regression, but they do give an insight in minimum and maximum values that are probably equal for all shoe sizes. As for the Forefoot cross intersection (see Figure A10.3), the spread is quite wide, ranging between 42 mm and 10 mm, although this could be an outlier. The heel cross intersection distal, on the other hand, stays below 12 mm. This data can be used to determine the spatial range of the sensors on the cross lines.

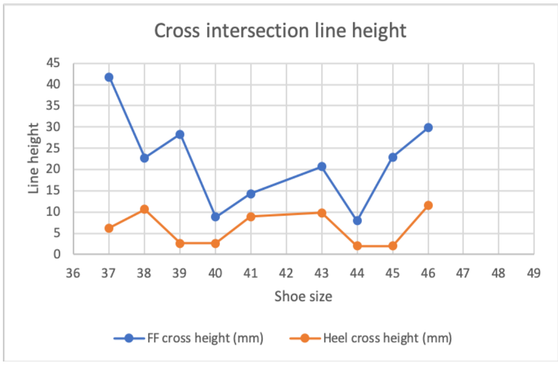


Figure A10.3: Cross intersection line height

3. Statistic analysis

Using a One-way ANOVA test, the factor Shoe size was compared to the foot dimensions, all of which are normally distributed. Significant correlations with shoe size were found for Heel-hallux length (P=0,001), Forefoot width (P=0,024), and Forefoot cross intersection distal (P=0,002). No significant correlation was found for Heel width, Heel cross intersection distal, heel and forefoot angle and heel and forefoot cross intersection medial.

Other significant correlations were found using a Pearson two-tailed T-test:
Heel-hallux length with Forefoot width (P=0,000), Heel width (P=0,000), Heel cross intersection distal (P=0,000), Forefoot cross intersection distal (P=0,000), but also to forefoot cross intersection medial (P=0,019) and Heel cross intersection medial (P=0,029).
Forefoot width with Heel width (P=0,000), Heel cross distal (P=0,000), Forefoot cross distal (P=0,019), Heel angle (P=0,020), Forefoot cross medial (P=0,000) and Heel cross intersection medial (P=0,001).
Heel width with Heel cross distal (P=0,001), Forefoot cross distal (P=0,000), Forefoot cross medial (P=0,004) and Heel cross medial (P=0,000).
Forefoot cross intersection distal with Forefoot and heel cross intersection medial (P=0,029 and P=0,026).

Conclusions framework analysis:

Shoe size can be used to predict Heel-Hallux length, Forefoot width and Forefoot intersection cross distal.
Heel-Hallux value can be used to determine Forefoot cross intersection distal (69-74% of H-H).
Heel-hallux length better predicts medial distance to Forefoot and Heel cross intersections with the heel-hallux line than shoe size.
Forefoot width and Heel width are highly correlated to each other and medial and distal cross intersection distances.
Surprisingly, Heel angle is correlated with Forefoot width
Forefoot cross line should be up to 40 mm thick to cover all participants anthropometric cross lines. Heel cross line can be as small as 10 mm.

4. Sizing chart

Table A10.1 shows the minimum required insole dimensions and cross line locations per shoe size to account for anthropometric differences. As can be seen, some shoe sizes have only small differences between dimensions, which can be clustered to a standardized value.

Clustering and combining multiple values leads to the clustering of new sizes ranging from XXS to XL covering sizes 37 to 48. Clustering of sizes will improve the manufacturing process and decrease its costs as fewer different items need to be produced.

Table A10.1: Insole dimensions based on size

	Insole dimensions (min)									
Shoe size	*EF (mm)*	*CB (mm)*	*AD (% of EF)*	*EH (% of EF)*	*FF cross height (mm)*	*EG (% of EF)*	*H cross height (mm)*	*Alpha (deg)*	*Beta (deg)*	**Size cluster**
37	230	90								XXS
38	250	100								XS
39										
40	270									S
41										
42	280	110	19	71	42	12	12	63	72	M
43	290									
44										
45										
46	300	120								L
47										
48	310									XL

5. Peak pressure locations

The coordinates of peak pressure locations as found in the Paraview data were used to calculate perpendicular distance to the participant's Heel-Hallux line and Cross

intersection lines (forefoot and heel). This is done to normalize the pressure locations according to the framework. These perpendicular distances were plotted in Figure A10.4 according to insole size clusters.

Visible in Figure A10.4a is a significant higher distance to FF cross among larger sizes, with a maximum of 65 mm above the line and 35 mm below the line. For the heel area, peak pressure locations are closer to the cross line with a maximum of 31 mm above the line and 35 mm below the line. After removing four outliers, some linearity becomes visible in pressure location spread (see Figure A10.5). To be able to detect all those peaks, the sensors should cover either at least 100 mm high around the forefoot and 66 mm around

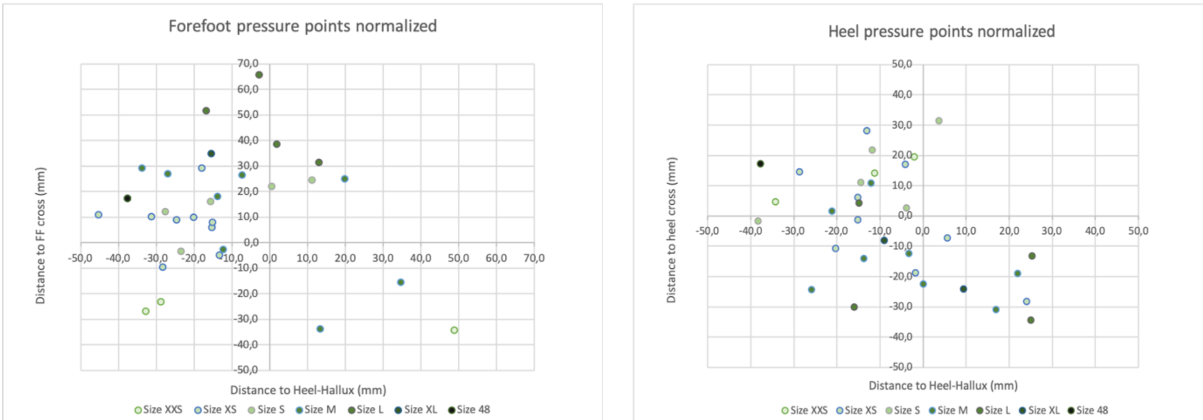
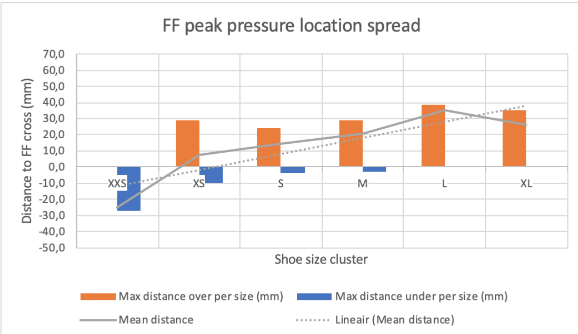
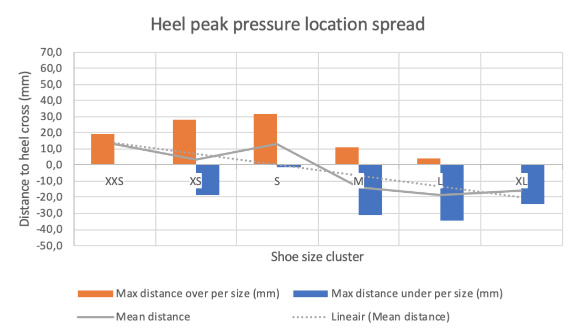


Figure A10.4: Pressure points scatter plots of forefoot (l) and heel (r) the heel, or the sensors (location) should vary between sizes.



a



b

Figure A10.5: Pressure location spread of forefoot (a) and heel (b)

Conclusions peak pressure analysis:
Larger foot sizes show peak pressure locations that are further away from the Forefoot cross line than smaller sizes, of which most of them above the cross line.
Larger foot sizes show pressure peaks located mostly underneath the heel cross line, where smaller foot sizes show pressure peaks located mostly above the heel cross line.
To cover all pressure peak locations, the sensors should be at least 100 mm high for the forefoot and 66 mm for the heel.
Sizes do not show a large difference in terms of transverse distance to Heel-hallux.
To cover all pressure peak locations, the sensors in forefoot should range to 45 mm lateral and 20 mm medial. In the heel area, they should range from 40 mm lateral to 30 mm medial.

6. Impact on design - Sensor locations

Sensors covering the Forefoot cross line should be up to 42 mm high to cover all participants anthropometric cross lines. Heel cross line can be as small as 12 mm.
The cross line angles should be 63 deg and 72 deg for the heel cross line and forefoot cross line respectively to cover the framework lines of all sizes.
To cover all pressure peak locations, however, the sensors should be placed higher or lower than those lines, depending on the size. Doing so, a sensor of only 40 mm high covers 82% of the peak pressure locations in the forefoot and 10 mm high covers only 58% of the peak pressure locations in the heel. However, increasing the sensor height to 50 mm for both locations, it will cover 96% (forefoot) and 94% (heel) of the peak pressure locations. For sizes L and XL, these sensor sizes would not suffice since they will not cover the forefoot cross line anymore. A larger or extra sensor would solve this problem.
To cover all pressure peak locations, the sensors in forefoot should range to 50 mm lateral and 20 mm medial. In the heel area, they should range from 40 mm lateral to 30 mm medial.
Sensors in the width of the foot do not need to differ between sizes.

Considering all these conclusions, a new sizing chart is proposed:

Table A10.2: Sizing chart proposal

Shoe size	Insole dimensions (min) EF (mm)	CB (mm)	Forefoot EH (% of EF)	Alpha (deg)	FF cross height (mm)	Sensor placement distance to FF	Heel EG (% of EF)	AD (% of EF)	Beta (deg)	H cross height	Sensor placement distance to heel	Size cluster
37	230	90	71	63	42	-10	12	19	72	12	15	XXS
38	250	100				0					7,5	XS
39												
40	270	110				10					0	S
41												
42	280					20					-7,5	M
43	290											
44												
45						30					-15	L
46	300	120										
47						40					-22,5	XL
48	310											

Figure A10.6 shows a new proposed sensor distribution, based on the sizing chart and conclusions.

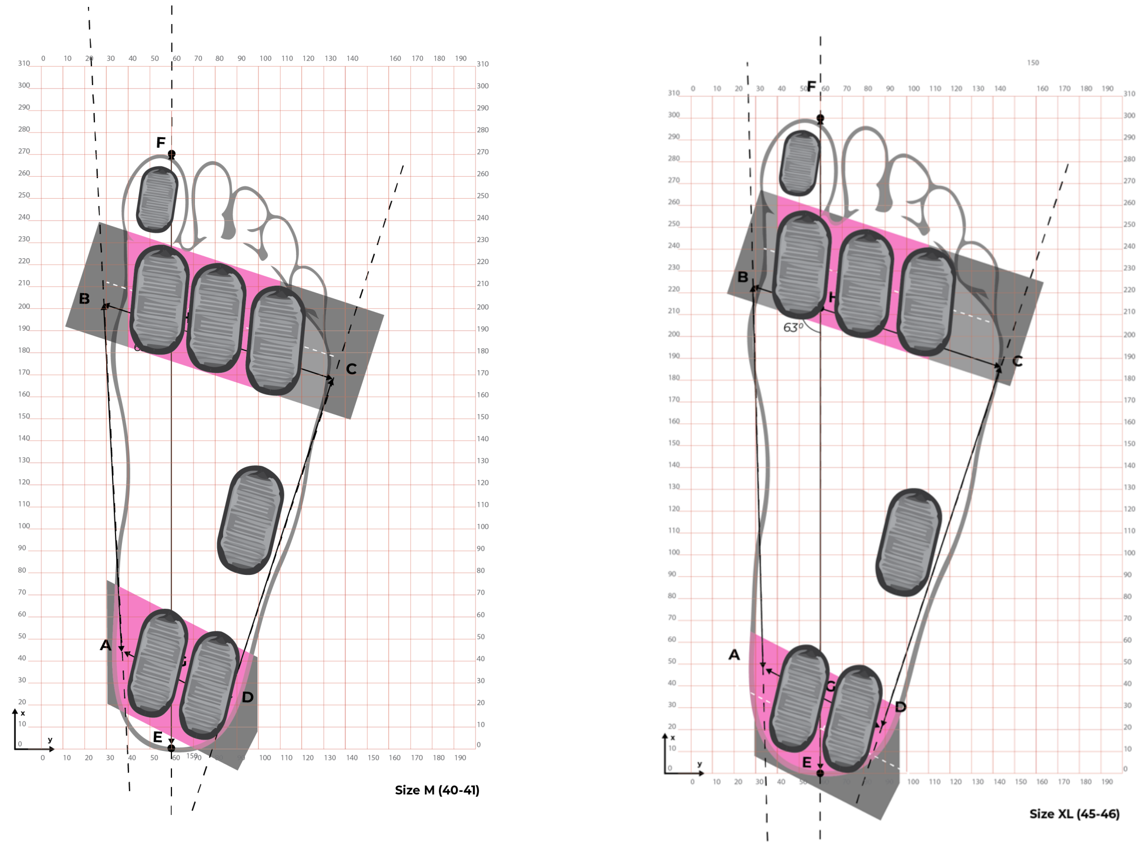


Figure A10.6: Proposed sensor distribution based on study results of size M (l) and size XL (r)

Appendix 11.

INTERVIEWS

Method

To validate literature findings and assumptions, expert consultations were done. Most interviews were performed in an informal setting, both by phone and in person. In most cases, the interviewee was contacted by email with a list of the questions that I wanted to ask. At the time of the interviews, the questions from the list were discussed and new questions that arose were discussed as well. Notes were taken on paper or a PC and written in my own words after the interview. For any follow-up question, the interviewee was contacted again.

Notes were used throughout the project mainly for my own understanding of literature and should be read in such a way, not to take formulations too literal

Index

Interview 1. Lotte Linssen

Lotte Linssen
Research Scientist, Exercise Physiology, Training & Performance Innovations bij TNO Soesterberg

Telefonisch interview op 19-09-2019

Met welke militaire groep doen jullie onderzoek? Welke groepen zijn er allemaal en wie zijn de bevelvoerders?

Wij zijn voornamelijk bezig met fysieke prestaties en optimalisatie van militairen, denk vooral aan kleding en uitrusting. Wat verhindert de mobiliteit? Werken met exoskeletten voor rugzakken. Ook cognitief. Maken modellen, hoe lang kunnen ze dingen volhouden etc. Laatst project voor nieuwe helmen obv antropometrie per individu. Ook koelvesten etc.
Landmacht (groene pakken) gaat het vooral om want is de grootste groep, koninklijke marechaussee (moeten veel staan), mariniers (valt ook beetje onder landmacht, behalve de Vloot). Je noemt een groep militairen een brigade, commandotroep of eenheid. Eenheid wordt het meest gebruikt. Eenheid heeft tussen de 20-30 man (denkt ze). (Groeps)commandant heet bevelvoerder. Nog specifiekere vragen weet Bertol van TGTF (trainingsgeneeskunde trainingsfysiologie van defensie). Dit is een tak binnen defensie (contactpersoon heet Bertol) die op trainingsfysiologie focust. Gaat ze me mee in contact brengen. Hij kan ook eventueel proefpersonen voor onderzoek regelen. TIP: vroeg aanvragen van proefpersonen, want duurt lang.

Hebben jullie data over het voorkomen van blessures (aantallen, oorzaken, welke militairen en impact er van)?

Inzoomen op specifieke blessures doen ze bij TNO niet veel. Ze hebben kort een project gehad over maatvoering van schoenen. In huidige situatie gaan ze langs een 3D scanner en moeten ze gewoon een maat opgeven voor schoenen. Er is een rapport over blessures, mag ze misschien doorsturen naar me!

Doen jullie labonderzoek naar looppatronen voor bijvoorbeeld selectie van schoeisel of orthesen?

Afdeling KPU is bezig met uitrusting, kan ze me ook informatie over geven. Juiste maatvoering is key.

Is er vraag naar verbetering in onderzoek voor blessurepreventie en zo ja, is daar budget voor? Denk bijvoorbeeld aan het persoonsgebonden KPU? Wie zou hier eventueel meer vanaf weten?

Er is zeker veel behoefte aan dit soort informatie. Ze doen nu veel met metingen over grote groep in plaats van individuen.
Arion hardloopzooltjes hebben ze wel eens gebruikt. Groot probleem: veel data en geen idee meer welke militair bij welk zooltje. Bertol kan hier meer info over geven.

Interview 2. Jos Schrijver

Jos Schrijver
Orthopeed en eigenaar bij Schrijvers orthopedie

Telefonisch interview op 23-09-2019

Jos zag mijn mailtje en vond mijn onderzoek erg interessant en relevant. Schrijvers orthopedie heeft een afdeling orthopedie en een sportwinkel in Overvecht, waar ze metingen doen en problemen kunnen aanpakken.

Ze doen veel schoenaanpassingen voor vakmensen zoals politie en ook militairen. Schoenaanpassingen zijn voornamelijk zooltjes en het ruimer maken van de schacht van de schoen (het bovenwerk). Dit laatste is misschien lastig met een zooltje te meten, maar eventueel met een sok?

Ze komen wel vaker langs pas als ze klachten hebben, niet vaak uit voorzorg. De politie biedt maar twee typen schoenen aan en dit is eigenlijk te weinig om te zorgen dat mensen geen last krijgen. Ook veel schoenen zijn helemaal plat, terwijl wandelschoenen bij de tenen naar boven krommen waardoor je beter afrolt. Militaire schoenen hebben dit vaak ook niet, waardoor dit problemen oplevert.

Veel voorkomende klachten:
Sommige mensen kunnen maar beperkt door hun knieën buigen en die kunnen last van hun voorvoeten krijgen. Dit kan je meten door de ROM te meten, maar er komt ook een hoge druk onder de voet, die je eventueel onder de zool kan meten. Dan moet er wel een bewegingstest worden gedaan.
Het afrollen van de voet geeft ook een goede indicatie van risicogevallen.
Je hebt ook holvoeten, die steunen niet in het midden van de voet. Dan sta je strak in de spieren en is er veel spanning aanwezig. Maar platvoeten ook dus. Knie klachten komen dan veel voor, enkels. Hielheffing is een oplossing voor een holvoet.
Te strakke/losse schoenen

Methodiek:
Ze maken bij Schrijvers een videoanalyse van het afrollen.
Ook zien ze veel aan de schoen waar een plooi ontstaat of het leer afslijt. Het zou zeer interessant zijn als je dit van tevoren kan meten zodat je de blessure voor bent. Er zijn wel eens producten met in-zool meting met drukprofiel die worden gebruikt voor schoenen uitkiezen. Hij heeft er in het verleden mee gewerkt, verzekeraars vragen er ook naar dus ze gaan er weer mee werken. Voornamelijk voor diabetes patiënten. Dan maken ze een zool op basis van een meting en dan testen ze de nieuwe zool weer met metingen van druk.

Bezoek bij de zaak op 03-10-2019

In dienst zijn 3 fysiotherapeuten en een bewegingswetenschapper. Het bedrijf is erg ambachtelijk in de zin dat ze veel analoog werken en op ervaring en gevoel te werk gaan. Ze werken niet veel met computers en al helemaal niet met getallen en waarden. Ze werken dus ook liever met analoge data. Met digitale data kan je zooltjes wel laten frezen, maar volgens Jos geeft dit minder hoge kwaliteit dan handmatig. Bij LFT footscan frezen ze wel zooltjes. Ook is het lastig rekening te houden met de binnenkant van de schoen. Een zool die plat is aan de onderkant past niet goed in alle schoenen waardoor de zool zijn vorm weer kwijt raakt.

Drie stappen:
Klacht beschrijving
Onderzoek naar bewegingsbeperking
Voetscan met LFT scanner en carbon druk

Met een carbon blauwdruk wordt duidelijk waar de druk hoog ligt. Bij diabetespatiënten kun je dus ook zien waar eventueel wondjes kunnen ontstaan. Ook maken ze wel eens een mal met een schuim blok. Hiervan wordt een gipsmodel gemaakt waar de schoen omheen wordt gebouwd.

Van meest naar minst voorkomende klachten bij Schrijver orthopedie (allemaal wel ongeveer evenveel)
Hielspoor (ontstaat door hoge druk bij heelstrike en weinig demping, ontsteking van aanhechting aan hiel en het kraakbeen dat gaat vermenen, kan ook ontstaan door overstrekken van de peesplaat onder de voet (plantaris). Holvoeten hebben minder flexibele pezen en spieren en krijgen meer last van overrekking van pezen zoals hielspoor. Ook iemand met overpronatie strekt pees meer.) Impact: kan heel lang duren als er een kraakbeen puntje is ontstaan. Operatie mogelijk. Hoge impact. Als je er vroeg bij bent kan je met een zooltje voldoende hebben (paar weken minder last maar altijd zooltje nodig). Anders spuit voor verweking of operatie (tot twee jaar niet meer kunnen trainen).
Voorvoetklachten (mortons neurogie of metatarsalgie (beknelling zenuw bijvoorbeeld bij spreidvoet en strakke schoen) / overbelasting / ontsteking / marsfractuur). Impact: beknelling zenuw kan maand of twee duren, marsfractuur kan ook maand of 3 duren.
Achillespeesklachten (dan ga je je enkel minder buigen als hij stijf is). Impact: maar paar weken duren als je hielheffing krijgt.
Kuitklachten. Impact zelfde als achillespees.
Scheenbeenklachten (voornamelijk shinsplints), krijg je bij korte/felle bewegingen. Bijvoorbeeld hoge acceleratie proneren of neerzetten). Impact: kan heel lang duren als het niet goed opgelost wordt. Als goed ontlast en beginstadium kan snel opgelost worden. Erge klachten gaat maanden duren of nooit meer kunnen lopen als te er.
Knieklachten (patellofemoraal en aanhechting klachten) / tibialis posterior. Overpronatie van knie ga je meten onder de voet mediaal bij de hiel. Impact: kan maanden duren, kan ook weken zijn.

De hardheid van de zool en schoen heeft veel invloed op hoe je loopt en de belasting op je gewrichten. Harde zolen zijn beter voor mensen die zwaarder zijn en een laterale stands hebben. Echter moet je wel voorkomen dat hierdoor de pronatie snelheid niet te hoog wordt.

Wat veel voorkomt is het doorknikken van de voet waardoor ook knie naar binnen proneert. Hierdoor ontstaat een knikvoet. Ook komt veel voor dat mensen gelimiteerd zijn in dorsaalflexie en dus de knie niet ver kunnen buigen. Hierdoor ontstaat hoge druk onder voorvoet tijdens lopen of kunnen de voeten erg naar buiten wijzen. Hoge belasting.

De inlegzooltjes die ze maken komen vanaf een zelfgemaakt halffabrikaat die vervolgens verwerkt wordt in verschillende standaard typen zooltjes en als laatste wordt afgewerkt om het passend te maken voor de individuele klant. Elke klant is verschillend en het is ook erg belangrijk dat je de zool aanpast op die persoon. Schoenen als Birkenstock en Teva hebben een voorgevormde zool, maar dit sluit niet aan bij iedereen en kan daardoor juist drukpunten veroorzaken.

De afdruk van de voet op ondergrond in 2D zegt wel veel over de hoogte van de voetboog, maar niet over drukverschillen. De combinatie geeft het beste effect.

Interview 3. Damien van Tiggelen

Damien van Tiggelen
Prof. Rehabilitation sciences Universiteit Gent en hoofdkinesitherapeut van het Militair Ziekenhuis Koningin Astrid in Neder-Over-Heembeek)

Telefonisch interview op 24-09-2019

Wat voor ervaring heeft u met militairen als onderzoeksgroep?

Wel eens met drukmeting (footscan) gewerkt, maar niet met krachtmetingen omdat dit moeilijk te verplaatsen is naar de kazernes. Verder nooit met zooltjes oid gewerkt. Techscan en dergelijke firma's maken zolen met druksensoren en genereren heel veel data waarvan heel veel niet relevant is.

Wat zijn veel voorkomende klachten onder militairen?

- Shinsplints
- Patalofemorale klachten
- Achillies tandinopathy
- Stress fracturen
- Bij ouderen ook lage rugpijn

Dit alles omdat schokken opvangen met gevechtslaarzen anders is dan sportschoenen. Omdat die laarzen niet gebouwd zijn voor comfort, levert dat veel problemen op.

Wat zijn interessante parameters om te meten buiten het lab voor deze gebruikersgroep?

Als de loop cadans te traag kan ook een indicatie zijn voor blessure. 150-160 p/m is te laag, moet op naar 170-180 passen p/m bij het rennen. Te trage cadans is te grote stap en te grote impact. IMUs (of accelerometers) zouden wel interessante informatie kunnen opleveren. Als dat geïntegreerd is in de laars (dus niet erop geplakt) want dat levert verschuiving op.

Wat wil je precies meten? Drukmetingen wordt veel gedaan maar hierdoor krijg je heel veel data waarvan veel niet relevant is. Met kracht sensor kan je misschien al genoeg meten. Inschatting: zo'n vier sensoren nodig? Hiel (lateraal/mediaal), bij afrollen (mediaal/lateriaal)?
Kadans en piek krachten kan je met kracht sensoren ook meten natuurlijk.
Je kan heel ver gaan, maar je moet je beperken. Maak het niet te moeilijk.

Wat is het verschil tussen rennen en marcheren (bij militairen?)

Er zit wel een groot verschil tussen rennen en marcheren. Techniek is anders. Heelstrike FF, MF, RF is wel het grootste verschil. De rest is niet relevant.
Wat is het verschil tussen mannen en vrouwen en hoe moet je dit meenemen in je onderzoek?
Voetmechanica verschillen tussen mannen en vrouwen nauwelijks verschil. 90% zijn sowieso mannen. Maar geen rekening mee houden.

Wie zou de data moeten kunnen inzien?

Elke eenheid heeft een sportinstructeur. Sportinstructeurs zouden de data moeten krijgen van hun rekruten. Zij kunnen de loopstijl aanpassen op basis van die data. Een tool om de cadans van een rekruut te corrigeren zou ook heel relevant zijn.

Zou Defensie vraag hebben naar een oplossing zoals ik die voor ogen heb? Wat zou dan een budget zijn?

Defensie zou zeker geïnteresseerd zijn om mee te werken aan innovatie. Indicatie: 200 euro per rekruut zouden ze niet riskeren zonder bewijst. Maar als ze weten dat ze daardoor veel letsels kunnen voorkomen en je bewijst dat je innovatie uitval kan voorkomen en hiermee geld bespaard kan worden is het wel interessant. Je moet hier wel een onderzoek voor uitvoeren. Dan kan het zijn dat het 300 euro mag kosten. Damien kan opzoeken hoe duur een militair in opleiding is en hoe veel er uitvallen. Met die info kan ik een schatting maken. Afdeling KPU oid zou hier meer van kunnen weten.

Wat moet ik meenemen in mijn onderzoek?

Je moet in kaart brengen wat de impact van gevechtslaarzen is. Bepakking speelt ook een grote rol. Je moet niet onderzoek gaan doen met sportschoenen. Damien kan me een paar gevechtslaarzen opsturen.
Je moet je onderzoek inrichten als een proof of concept. Een kwaliteitsstudie. Dan maak je een mooie stap.

Jullie hebben Cox regression analysis gebruikt voor analyse. Is dit een goede methode voor mij om te gebruiken of is dit alleen voor langere termijn? Welke andere methoden om verband te leggen tussen biomechanische parameters en blessure is aan te raden? Bijvoorbeeld tests doen met personen die in het verleden een bepaalde blessure hebben gehad?

Cox regression analysis is relevant als je de tijdsvariabele hebt. Als je een kwaliteitsstudie doet is dat niet relevant. Het zou de volgende stap zijn om je zooltjes te testen met blessures en tijdsvariabelen over langere termijn (niet binnen je afstuderen). Je moet eerst je product vergelijken met bijvoorbeeld een krachtenplatform. En een retrospectieve studie? Bij een retrospectieve studie heb je het probleem dat ze misschien anders zijn gaan lopen juist door de blessure.

Interview 4. Bertil Veenstra

Bertil Veenstra
Staf Commando Landstrijdkrachten / Afdeling Trainingsgeneeskunde & Trainingsfysiologie

Telefonisch interview op 11-10-19

Stel er wordt afgelezen dat een individu hoog risico voor blessure vertoont, naar wie moet deze informatie en naar wie vooral niet? Sportinstructeur? Commandant?

Fysiotherapeuten gaan het dan gebruiken om te meten tijdens marsen. Ze doen het wel met loopbanden. Ook ooit zooltjes gebruikt. Maar dit was voor een totaal ander doeleind (bepakking wegen).

Wat voor budget moet ik aannemen voor een product proposal per recruut?

Dit hangt erg af van wat het product allemaal kan. Als het bewezen is dat het uitval van rekruten verminderd is daar geld voor over. Nu niks over te zeggen.

Over zijn huidige project:

Ze zijn al enkele jaren bezig met insole met Universiteit twente en een bedrijfje hier voor. Dit blijkt erg moeilijk. Niet voor loopanalyse, maar het gewicht van de bepakking meten. De grootste challenge zit hem in vertalen van drukverdeling naar kilo's bepakking is moeilijk. Dit om te weten wat hun fysieke belasting is. Zonder dat ze er bij zijn willen ze aan het einde van de week kunnen weten hoeveel bepakking, hoeveel energie, hoeveel geslapen, hoe snel gelopen, met lichaamsgewicht als constante. Dit project loopt niet erg soepel en zou best wat ondersteuning kunnen gebruiken.

Als je load kan meten (bepakking etc) totale gewicht wat iemand draagt dan zou defensie daar erg veel aan hebben.

Ze doen bij defensie al statische meting. Wat ze daar uithalen weet Bertil niet.

Over mijn project:

Iemand 100m laten lopen met bepakking weet je al genoeg, met vermoeidheid moet je langer lopen
Je moet vooral nadenken over schade voorkomen bij intensief gebruik. Andere locaties van sensoren tov andere meetzooltjes weet hij niet of dat nodig is.
Je moet zorgen dat je geen data verliest omdat je daar geen sensor hebt.
Draadloos data uitlezen kan prima veilig. Vooral tijdens training.

Uitdaging:

Warmte en vocht problemen en stuk gaan van kabeltjes.
Ergonomisch en comfortabel
Is de data stabiel of verandert dit onder invloed van warmte, vocht, gebruik. Moet je het telkens kalibreren?
Als je de data goed binnen krijgt, wat doe je er dan mee?

Email contact op 21-10-2019

Bij welke militaire groepen komen de meeste blessures voor? (bv. landmacht, nieuwe rekruten, etc)
Ik heb geen harde cijfers om dit te onderbouwen en lijkt mij af te hangen van het type blessure. Dat gezegd hebbende lijken leerling militairen mij het meest voor te komen in de overbelastingsstatistieken.

Hebben jullie data over het voorkomen van blessures (aantallen, oorzaken en impact ervan)? Als het vertrouwelijk is, is een indicatie genoeg. Bijvoorbeeld welke activiteit is het meest belastend? Lange marsen, hoe lang?

Wij hebben geen data over dit onderwerp. De data bestaat echter wel, maar wordt beheerd in het GIDS (elektronisch patiënten dossier). Deze is niet voor mij direct inzichtelijk.

Worden er momenteel maatregelen genomen om blessures te voorkomen?

Preventieve maatregelen zijn onder meer een functionele aannamekeuring, de leerling monitor (fieldlab), het schoenenprotocol en opbouwprotocollen in fysieke lesprogramma's.

Wat wordt er gedaan met een geblesseerde militair? Hoe vaak komen militairen bij een arts? In welke mate helpt defensie met het ondersteunen van blessures? (bv hersteltraining, aanschaffen van steunzolen etc)

De geblesseerde militair valt terug om de militaire gezondheidszorg organisatie. Deze heeft een inrichting die erg lijkt op de civiele organisatie: de huisarts is de poortwachter en het tweede echelon is beschikbaar op verwijzing. De fysiotherapeut en bedrijfsarts zijn beschikbaar in de eerste lijn. Hier worden kortdurende inzetbaarheidsbeperkingen gegeven. Daarnaast bestaat de mogelijkheid om een langduriger opwerk/train protocol te volgen. Dit heet dan "fysiofit" of "sportfit".

Wat is jullie ervaring met meetzooltjes? Handig in gebruik? Data specificatie en presentatie relevant? Prijs/kwaliteit?

Wij laten de zooltjes maken bij de Orthopedie Techniek Aardenburg (OTA). Zij leveren de zooltjes op indicatie aan de militairen. Ik ben niet bekend met de verschillende merken en prijzen.

Welke variabelen kunnen we vast zetten binnen een training programma? Bv. Worden marsen herhaald door verschillende eenheden, standaard loopsnelheid, standaard bepakking, schoeisel. Deze vraag stel ik omdat je dat kan gebruiken om metingen met elkaar te kunnen vergelijken en daar conclusies uit kan trekken.

Marsen hebben veelal een standaard verhouding: 60 minuten marsen – 10 minuten rust – 60 minuten marsen – 10 minuten rust – 60 minuten marsen – 20 minuten rust – en dat herhaalt zich. Er zijn uiteraard wel variaties in draaglast en tempo mogelijk. Er worden ook meerdere typen schoeisel. Over het algemeen zijn er een stuk of 5 gangbaar. Het fysieke programma van een eenheid is tamelijk vast beschreven, maar verschilt uiteraard per eenheid. Dit is dus wel van tevoren in te schatten. Ik heb hier geen inzicht in.

Zijn er andere parameters die jullie graag zouden weten van militairen die ik eventueel kan toepassen in mijn ontwerp?

Ik denk dat de vraagstelling nu te breed is. Het lijkt me zinvol om eerst een probleem te definiëren, een belangrijke of veronderstelde causale factor te onderkennen en dan te beoordelen of deze factor daadwerkelijk een causale relatie heeft met het probleem (met een voorzet hoe deze op te lossen is). Concreter voorbeeld: onderbeenklachten zijn een evident probleem. Marstempo is een veronderstelde causale factor. Beoordeel de relatie tussen het marstempo en de incidentie van onderbeenklachten (en identificeer eventuele verstorende factoren in de relatie).

Interview 5. Tycho ter Hark

Tycho ter Hark
Werkt bij de Landmacht (logistiek)

Telefonisch interview op 18-10-2019

Kan je kort vertellen wat je precies doet bij defensie?

Hij zit al 6 jaar bij landmacht en studeert psychologie er naast. Werkt bij logistiek en als vertrouwenspersoon.

Kan je me informeren over de basis trainingsprogramma's voor nieuwe rekruten? (Is er een standaard trainingsprogramma dat alle nieuwe rekruten moeten afleggen? Hoe heet die dan en hoe lang duurt die?)

Je hebt de algemene militaire opleiding voor elke rang. Officieren, onderofficieren en manschappen, deze moeten allemaal de algemene opleiding doen. Vroeger was deze opleiding drie of vier maanden en nu is hij iets langer dan een maand. Verschillende sport trajecten. Als je voor een zwaardere functie solliciteert, krijg je hierin zwaardere training. 2 of 3x per week sporten. Begin en het eind is een dsp test (12 minuten zo veel mogelijk meters maken). Ook een 5 km mars op kisten en volle bepakking. Hindernisbaan etc. Dit is als ze algenomen zijn, maar wel begin van de opleiding.
Bij werving en selectie heb je een medische keuring. Hierin zitten gesprekken en capaciteiten test. Hier kijken ze ook naar je voeten statische druk test en op hometrainer etc. Dat is de nulmeting en gaan ze je inschalen naar je ambitie bij defensie.

Wat voor schoeisel hebben jullie en wat is je ervaring er mee? Krijgen jullie inzooltjes als je last krijgt?

De nieuwe Haix schoenen worden algemeen niet als prettig ervaren. Je kan wel zooltjes aan laten meten. Dit wordt in Doorn gedaan. Die kijken niet naar drukmeting en schokbelasting. Oude Meindl schoenen zijn afgekeurd en nu zijn er nieuwe van Haix. Haix heeft een winter model (nat weer model) en multi-climate model. Hetzelfde model maar dikkere Gorex laag.

Merk je dat er veel overbelasting blessures ontstaan bij lange marsen?

Hij heeft zelf nog nooit een blessure gehad, maar wel vele mensen om hem heen. Heeft meerdere oorzaken. Veel schokbelasting op je knieen. Door marsen en tactisch verplaatsen (marsen in drijggebieden). Schokbelasting groot. Veel knie blessures en rugblessures.

Als er data verzameld kan worden over foute looppatronen, bij wie zou die informatie volgens jou verzameld worden?

Alle krijgsmachten komen bij blessures naar hetzelfde revalidatiecentrum, dit zit in Doorn. Zoals fysiotherapie en onderzoek als blessures terug komen. De mensen in Doorn zouden heel veel baat hebben bij informatie over drukmetingen tijdens marsen. Tycho gaat proberen een contact te zoeken voor me. Je zit wel met privacy wetgeving, dat moet je even uitzoeken of navragen bij hen.

Tweede telefoongesprek (29-10-2019)

Hoe werken jullie in communicatie naar elkaar? Achternamen, ID nummers?

Achternaam, rang en met u.

Hebben jullie telefoons en gebruiken jullie die tijdens kazerne week?

Soms mag hij niet mee. Tijdens een pauze mag je wel op je telefoon. Leidinggevenden kunnen de telefoon bevelen mee te nemen.

Waar ga je heen als je last hebt van iets? Denk je dat veel soldaten dit niet doen / klachten negeren?

Leidinggevende (mars leider of commandant) als eerste. Die bepaalt hoe ernstig het is. Die kan ook vervoer regelen.

Ken je een soldaat die een blessure heeft (gehad?) zou ik die mogen spreken?

Ja gaat hij regelen.

Hoe lang duurt een lange mars? (bv langste mars en kortste mars)

Langste mars is 40 km (vierdaagse). 2km. 40-45 km is 8-9 uur. Eindoefening van militaire opleiding is maximaal 20-25 km, met opdrachten tussendoor dus kan ook twee dagen duren.

Kan je een beeld schetsen van een typische dag van een lange mars?

Opladen moet voor de mars gebeuren, dat kan niet tussendoor.
Soms gaan ze overdag marsen, soms midden in de nacht en dan vertellen ze het niet. Marsen wordt gedaan in opwerktraject. Van 5 km zonder bepakking naar 20 km met bepakking. Ligt ook aan de functies.
Slapen op een kazerne. Ze worden gewekt of zelf wekken ligt aan afspraken. Meestal een bepaalde tijd afgesproken om te verzamelen voor het gebouw en moet je alles aan en mee hebben en hebben gegeten. In bloktijden eten in eetzaal. Je gaat dus samen eten op een bepaalde tijd. Rugtas dag van tevoren gepakt. Er zijn ruimtes waar de zooltjes opgeslagen zouden kunnen liggen. Na de mars: Douchen en omkleden. Misschien nieuw programma er na.

Wat doe je met je schoenen na een lange mars? (bij je bed, bij de deur?)

Bij je bed of in de kast bij je bed. Iedereen heeft een persoonlijke kast.

Interview 6. Sander Dokter

Sander Dokter
Werkt bij Defensie (logistiek), heeft blessure gehad

Telefonisch interview op 31-10-19

Hoe lang werk je al bij Defensie en welke functies heb je (gehad)?

25 jaar bij defensie. Alleen maar logistieke functies. Veel bureauwerk en rijden. En twee algemene militaire opleidingen gedaan. Soldaatopleiding: 6 maanden en een voor onderofficier opleiding: 9 maanden 15 jaar later.

Doe/deed je iets er naast of zit je full-time bij Defensie?

Nee altijd fulltime defensie

Wist je tijdens je algemene militaire opleiding al wat je wilde worden?

Nee. Ik werd opgeroepen als dienstplichtige, en ben blijven hangen. Heb georiënteerd binnen landmacht wat me interessant leek. Logistiek gekozen omdat het me leuk leek en zodat ik niet te veel intensief hoef te lopen en in het bos hoef te slapen.

Hoe oud was je toen je startte met de algemene militaire opleiding?

19 jaar

Hoe lang duurde die?

6 maanden, nu zijn ze 3 a 4 maanden.

Wanneer raakte je geblesseerd en waaraan?

2010 tijdens onderofficiersopleiding. Kraakbeen versleten aan de voorkant van mijn knieën. Dit is operatief behandeld. Helemaal aan het eind tijdens de eindoefening tijdens mars van 40 km en 60 Kilo bepakking. Pijn bouwde langzaam op, had al beetje last van. Zei er niks van (veelal door luiheid) en dacht dat het wel weg ging.

Is dit een beetje een algemene houding onder militairen (niet snel iets zeggen als ze last hebben)?

Tegenwoordig gaat iedereen wel rap naar een dokter als ze ergens last van hebben. Cultuur is een beetje veranderd. Misschien zijn ze bang om lang er uit te liggen. Zorgaanbod Is ook hoger en meer specialisten en gepersonaliseerde kleding en dergelijke. Goed geregeld, alles is aangepast.

Wat is denk je de oorzaak van je blessure geweest?

Combinatie van overbelasting (40 km en 60 kilo rugtas) en misschien iets aan looptechniek.

Waar heb je gerevalideerd en hoe lang?

Na operatie in het CMH naar revalidatiecentrum in Doorn gegaan, 4 maanden opgewerkt om knie maximaal te kunnen gebruiken.

Hoe zag deze revalidatie er uit?

Looptechniek is gemeten aan het begin en was op dat moment goed. Moest op een loopband staan met sensoren en keken ze hoe de afwikkeling van mijn voet was.

Het is zeer goed geregeld, rustig beginnen met bewegen, veel 1-op-1 begeleiding. 5 dagen in de week moest ik daar zijn en dan kan je daar ook slapen in bungalowtjes. 15 man zat daar toen te revalideren met verschillende blessures. Sommige oefeningen doe je samen (zoals zwemmen). Sporten is 1-op-1 begeleiding. Zowel fysiotherapeuten en sportinstructeurs doen deze begeleiding. De sportinstructeurs zijn dezelfde als de andere soldaten krijgen. Training is o.a. zwemmen, hardlopen en krachtoefeningen. Ook dingen als houtbewerking. Alles om je knieën te belasten.

Aan de hand aan je fitness oefeningen meten ze of je vooruit gaat. Zolang je maar pijnvrij blijft. Maar 1 keertje de meting gedaan aan het begin, daarna niet meer.

Heb je nu nog last van de blessure? / Ben je anders gaan bewegen door de blessure (bijvoorbeeld ter preventie)?

Nee, helemaal over. Niet aan de orde. Na operatie was het vrij snel over.

Wat vind je belangrijk als het gaat om blessure preventie en herstel? Wat verwacht je van de begeleiding en Defensie in het algemeen om hiermee om te gaan?

Goede begeleiding na blessure en veel terugkoppel-momenten. Ondervind je nog nasleep? Dat soort dingen. Ook ná herstel af en toe (halfjaarlijks) terugkoppeling hoe het gaat. Dit gebeurt nu wel, maar niet heel veel. Gaat via telefonische afspraak. Telefonisch contact werkt prima. Dit contact had ik met het CMH hospitaal in Utrecht.

Hoe hebben jouw officieren (leidinggevenden) contact gehad met jou en je herstelbegeleiding?

Medici hebben contact gehad met mijn officieren over mijn voortgang en die zijn ook 1x in de maand langs gekomen. Dit vond ik wel fijn dat ze interesse hadden en ik niet gewoon als nummertje wordt gezien.

Heb je eronder geleden dat je een blessure had (financieel, emotioneel)?

Nee nergens onder geleden. Je krijgt gewoon 100 % van je salaris doorbetaald. Niet moeilijk, ik zit daar voor mezelf. Er is geen psychologische hulp voor blessures zoals dit denk hij. Misschien als je er om vraagt wel.

Vind je het belangrijk op de hoogte te zijn van je eigen fysieke gesteldheid?

Zou fijn zijn om zelf fysieke gesteldheid in de gaten te kunnen houden is goed. Fitness trackers zouden wel worden gebruikt door veel mensen verwacht hij.

Interview 7. Christian Linschoten en Naomi van Valderen

Lkol-arts W.O. Zimmerman (interview met assistenten Naomi van Valderen en Christian Linschoten)
Sportartsen van TGTF bij Militair Revalidatie Centrum (MRC) Aardenburg

Persoonlijk interview op 02-12-19

Christian is arts en Naomi is arts in opleiding en ze zijn beide ook reservist.

Blessures bij Defensie

Hoe doen jullie lab onderzoek naar looppatronen (voor bijvoorbeeld selectie van schoeisel of orthesen)?

Verschillende tests zoals pronatie tussen zitten en staan (hoogte van de voetboog opmeten met liniaal). Daarnaast wordt er een video opname gemaakt met een instrumentale loopband waar ook drukmetingen onder de voet worden gedaan. Die meting is slechts een gemiddelde van voor, midden en achtervoet. Deze kijkt niet naar bijvoorbeeld mediaal en lateraal. Het systeem print grafiekjes van druk waarop een interpretatie van de VLR wordt afgelezen, echter wordt hier geen numerieke waarde aan vastgehangen. Dit zouden ze wel graag willen (aldus Christian). Op basis van de drukmetingen en videoopnames wordt een besluit genomen of de patient looptraining moet gaan doen of dat er verder medisch onderzoek wordt gedaan.

Gedurende de therapie wordt ook gebruik gemaakt van subjectieve enquetevragen volgens de SANE methode. Er wordt gevraagd naar een beoordeling van eigen fitheid van de onderbenen op een schaal van 1-100. Dit wordt echter sterk gebiased door de koppigheid van militairen, die niet snel zeggen dat ze ergens last van hebben.

Hoe denken jullie dat de meeste OLLI blessures ontstaan tijdens algemene militaire opleiding?

Verkeerd lopen en verhoogde belasting door de kisten.

Wat voor trainingsprogramma is er voor mensen met verkeerd looppatroon? Of wordt dit alleen voor herstel gedaan?

Ze hebben bij TGTF een looptrainingsprogramma. Deze duurt enkele weken. Er wordt gefocust op voorvoet landing, kleine stappen zetten en rechte houding. Hier mag ik een keer bij zijn.

Doen jullie verder nog onderzoek?

Ja op dit moment zijn we zeer geïnteresseerd in het achterhalen of de looptraining zinvol is. Oftewel, wordt er buiten het lab ook goed gelopen? Op de langere termijn willen we er achter komen of we blessures kunnen voorkomen.

Werken met zooltjes / metingen

Hebben jullie ooit gewerkt met meetzooltjes? Waarom zijn de zooltjes niet goed voor grootschalig onderzoek?

Weten ze niet. Zij kunnen zicht niet herinneren dat er iets anders is gebruikt dan de loopband.

Hoe werken jullie met veilige data communicatie? En AVG? Hoe kan je een profiel anoniem maken? Mag data van zooltjes en blessure incidentie gebruikt worden voor machine-learning?

Het is een goed idee de data te gebruiken om het systeem slimmer te maken. We zijn hier ook veel bezig met dingen als apps en live terugkoppeling. Er wordt ook onderhandeld over een mogelijke samenwerking met Garmin. Bertil Veenstra weet hier meer vanaf.

Zou de data die voortkomt uit metingen van militairen gebruikt mogen worden voor nieuwe gebruikersgroepen in de toekomst?

Vragen aan Veenstra of de Jong

Mijn onderzoek

Is er vanuit Defensie vraag naar projecten zoals dit en hoe worden deze zoal gefaciliteerd? Intern/extern? Onderzoek? Financiering?

Ja ze zijn hier altijd op zoek naar mensen met een technische achtergrond om dit soort projecten te ondersteunen. Wij zelf doen veel onderzoek naar de medische kant van jouw verhaal. Naomi gaat binnenkort beginnen met een promotietraject over het voorkomen van blessures bij de militairen. TNO doet ook veel onderzoek. Wel zeggen ze dat een onderzoek als dit niet makkelijk veel meer support zal krijgen. Dus het zal geen budget toegewezen krijgen voordat de relevantie en werking bewezen zijn.

Interview 8. Marnix de Jong

Marnix de Jong
Projectmanager DTCS bij Defensie

Persoonlijk interview op 15-01-2020

Wat is Defense Training & Coaching System?

Een project dat binnenkort start waarin militairen een platform wordt geboden om hun training te stimuleren en ondersteunen. Door middel van verschillende producten van verschillende merken (zoals hartslagmeter, sport horloge, etc) wordt data verzameld die door een speciaal horloge worden ontvangen (bluetooth) en verwerkt (DS&OW). Deze data wordt via de app of horloge zelf terug gekoppeld naar de gebruiker. Met toestemming van de gebruiker wordt de data ook gedeeld met zijn sportinstructeur, die vervolgens inzichten krijgt over individuen en groepen waar deze militair tot behoort. Hiermee kan hij/zij een trainingsprogramma plannen. Ook kunnen gebruikers elkaar uitdagen in trainingen en hun resultaten met elkaar delen. Tenslotte wordt beoogt de resultaten ook in te zetten om inzetbaarheid van individuen en groepen te toetsen voor verschillende operaties. Op het moment wordt fitheid alleen gemeten met een systeem dat Cognos heet en een ander dat AMF (algemene militaire fitheid).

Om dit project succesvol te maken gaan we uit van een less-is-more principe. Als er te veel data gepresenteerd wordt, is dit niet bruikbaar. Daarom werken we met een beknopte lijst aan parameters. Het is ook belangrijk terugkoppeling genoeg te variëren. Als iemand elke dag te horen krijgt dat hij 10.000 stappen heeft gezet interesseert het hem op een gegeven moment niet meer. Op de lange termijn zal het concept van machine-learning of AI komen kijken.

Gebruiken militairen (in algemene opleiding) een vorm van (wearable) physical monitoring? Zo ja, welk type? Wordt dit centraal geregeld of moeten individuelen dit voor zichzelf regelen? Wordt het alleen gebruikt door revalidanten of ook door fitte militairen? Werkt Defensie al samen met een extern (of intern) data analyse/verwerking bedrijf of activity tracking merk zoals Garmin?

Het DS&OW sporthorloge is nog in ontwikkeling en wordt waarschijnlijk opgepakt door bijvoorbeeld Garmin of Sunto. Daarnaast staan op verschillende plekken biomechanische weegschalen en vetpercentage meetapparatuur om door gebruikers zelf te worden gebruikt. Hier log je in waardoor de data op je digitale profiel komt te staan. Overige producten zijn hartslagmeters en andere meetinstrumenten. Deze worden niet actief verspreidt maar wordt binnenkort wel gestimuleerd om gebruikt te worden.

Communiceert een arts/therapeut van een patiënt met zijn/haar sport instructeur en leidinggevende over revalidatie voortgang? Hoe? Zo niet, zou dit moeten? Kan de communicatie verbeterd worden? Wat is ideaal?

Het DTCS systeem verbind de sportinstructeur (aan een kant) met de militair en andere collegas. Behalve persoonlijke ontmoetingen heeft het systeem ook een messenger functie. In een revalidatie proces is er een heel ander traject dan een fitte militair. Daar communiceert de militair met een arts, die verbind hem/haar door naar een fysio of sportorganisatie. Bij een sportorganisatie heb je nog onderscheid in fysiofitheid en sportfitheid. Bij het laatste ben je weer inzetbaar. Binnenkort komt er een lifestyle coach aan te pas die individueel ook met militairen contact kan hebben (bijvoorbeeld via het platform).

Welke maatregelen worden genomen om activity-monitoring data of medische meet data veilig op te slaan en te delen? Vooral in het geval van draagbaar meet apparatuur zoals een Garmin horloge.

De AVG wetgeving kent verschillende rubrieken binnen dataveiligheid. Wanneer data 'medisch' is (dwz iemand met een BIG certificaat heeft de data opgemeten) dan is die data geheim en mag deze niet zomaar gedeeld worden. Als een gebruiker zelf data opmeet is dit makkelijker. Het is wel bij wet verboden als werkgever te vragen aan werknemers metingen te doen, behalve bij Defensie ten behoeve van inzetbaarheid. Wij werken in het DTCS systeem met privacy by design. Als default is de data alleen bereikbaar voor de gebruiker, maar er wordt wel gevraagd (en gestimuleerd) dat de data gedeeld wordt met sportinstructeur en collega's zodat hun training efficiënter wordt en er meer motivatie gecreeerd wordt.

Zodra ze een knop én een vink zetten dat ze de terms & conditions hebben gelezen heb je toestemming om de data de delen. Ook kunnen ze hem tijdelijk aan of uit zetten.

Als loop-data wordt afgenomen van militairen voor onderzoek en hier relevante resultaten uitkomen, zou die data gebruikt mogen worden voor implementatie in nieuwe gebruikersgroepen in de toekomst? Waar moet hier rekening mee worden gehouden wat betreft data en privacy veiligheid?

Ja want het product is van een extern bedrijf. In het algemeen zijn er drie zaken waar het DTCS programma mee te maken heeft:

Defensie beveiligingsbeleid, zoek hiervoor naar een ABDO document. Dit wordt gebruikt om TBB te bepalen.

AVG wetgeving

Europese aanbestedingswetgeving. Deze wetgeving is voor overheidsbedrijven (zoals defensie) die concurrentie waarborgt voor inkopen van producten boven de 125.000 euro.

Waarom worden er op het moment geen meetzooltjes gebruikt?

Er is ooit een onderzoek gedaan naar meetzooltjes om bepakking te meten in het veld (door Bertil Veenstra). Dit had een heel ander doel dan DTSC. Het product meetzooltjes bestaan al en is geen rocket science, maar de algoritmen om het product hier inzetbaar voor te maken is het unique selling point en is cruciaal om hier gebruikt te kunnen worden. Die zijn op dit moment niet beschikbaar.

Interview 9. Lars Fuit

Lars Fuit
Podotherapeut Fuit & van Houten

Persoonlijk interview 07-01-2020

(Algemene feedback na het uitleggen van mijn project)

Je moet er rekening mee houden dat ieder individueel op een heel andere manier loopt en beweegt. Dit is omdat het lichaam zich aanpast aan andere delen van het lichaam. Stel dat iemand zijn ene been langer is dan het andere, gaat hij/zij misschien asymmetrisch lopen. Dit wil niet per sé zeggen dat hij/zij verkeerd loopt, maar dat zijn dynamiek en misschien ook wel bouw zijn aangepast aan zijn dat lengteverschil. Abnormaliteit is dus niet altijd iets slechts.
Maar wat gebeurt er als iemand met zo'n abnormaliteit of asymmetrie zichzelf aan hoge belasting blootstelt zoals bijvoorbeeld in het leger. Blijft dit dan nog steeds onopgemerkt / ongevaarlijk?
Dat zal in sommige gevallen wel zo zijn en in andere niet.

Wat zijn de parameters die interessant zijn om te meten voor een podotherapeut én om inlegzooltjes te kunnen maken?

De allereerste impact piek. Je moet er op letten dat de éerste impact piek binnen 20 milliseconden plaatsvind en heel kort is, dus je meetapparatuur moet dit kunnen waarnemen. Daarna volgen pas de twee pieken van hak en voorvoet. Die eerste piek zegt ook veel over belasting bij het neerkomen en die heb je niet meegenomen als je alleen naar de twee grotere pieken kijken. Deze eerste piek is vaak ongeveer 3x het lichaamsgewicht bij lopen.

Welke parameters kan ik niet meten die wel belangrijk zijn?

Je neemt nu nog niet statische disbalans mee. Als je iemand 10 minuten stil laat staan krijg je een goed beeld bij zijn verdeling tussen links en rechts en voor en achtervoet die je bij lopen minder goed ziet. Als iemands been aan een kant korter is zal je dit zien bij een statische meting. Een verschil in beenlengte kan bij veel wandelen (zoals marsen) problemen in de rug en heupen veroorzaken.

Wat vindt u van het ontwerp van de meet-zooltjes, denkt u dat ze geschikt zijn voor medische toepassing?

Van de metatarsals zeggen M1, M2 en M5 het meest, die worden goed gecovered. M3 en M4 volgen de anderen een beetje, die hoef je dus niet los van elkaar te meten. De sensor bij de kleine tenen is niet echt nuttig. Er mist er misschien wel eentje op de middenvoet. Nu je maar één sensor hebt in de middenvoet heb je dus geen informatie over mediaal-laterale verplaatsing in dit gebied. Sommige mensen proneren in hun middenvoet en dit zal je dus niet kunnen meten. Hier zou ik een sensor bij doen. Echter is het dan dus wel belangrijk dat de balans-lijn ongeveer midden tussen twee sensoren zit dus misschien moeten de sensoren smaller worden.

Wat voor informatie zou je willen ontvangen om (zonder een patient bezoek) een inlegzooltje te kunnen maken?

Het produceren van een inleg zooltje op basis van drukmeting data is eigenlijk niet te doen. De zooltjes worden ontworpen op basis van functieonderzoek, statische meting en houding en dynamische metingen en observaties. Je kan niet genoeg data halen uit slechts de meetzooltjes om een kwaliteit inlegzooltje te maken.