The impact of perceived comfort of weighted shoes on kinematic and kinetic parameters in the running gait

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Abstract

The aim of this study has been to measure the impact of shoe weight on perceptions and their relationship with running gait parameters. The fluctuation of the kinetic (e.g. pressure distribution), kinematic (e.g. knee angle) and subjective parameters (e.g. perceived weight) have been analysed by changing the shoe weight. More in detail, it has been tested whether there is a significant difference between the graduate increase and graduate decrease of the shoe's weight perception and movement pattern in the gait cycle.

Eighteen healthy participants (age: 25±2 years; height: 179±7 cm; body mass: 74±6 kg) without lower extremity injuries have taken part of the experiment. All the subjects were not professional runners but they practice sports at least 3 hours per week. Subjects have run on a treadmill at 10 km/h for 16 times during 2 minutes. In the first eight the shoe weight was increased from a neutral condition (N: 350 grams) to a weighed one (A: +50 grams; B: +150 grams; C: +315 grams) or to the neutral again (N) in a randomized order. The second phase has been performed in the opposite direction, from a weighed shoe to a neutral one (A→N; B→N; C→N; N→N). Whereas the kinetic parameters have been recorded with Moticon system, motion capture Vicon has been used to collect the kinematic evolution.

Kinetic results have shown differences between the neutral condition and the weighted ones: increase of the cycle time, swinging phase and the reduction of the contact time for the heavier shoes. In addition, the maximal knee angle during swinging phase tends to be larger when the shoe weight increases. It has been interpreted as an unconscious reaction of the body to make the steps more stable.

Subjective results revealed no statistical differences when the shoe order is changed. This study confirms that people detect heavier shoes easily from 150 grams onwards. Perceived weight results converge in the 315 grams for the first and second phase. Objective and some subjective parameters (knee angle, COP distance and velocity) have shown this pattern and it has been declared that perceptions have an effect in kinematic and kinetic parameters.

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1. Introduction

There are more than 3,000 sports disciplines and games all around the world (Liponski, 2003) and for the vast majority, a pair of shoes are needed. One of the most popular sports currently is running. A study made in 11 European Countries estimates than 50 million Europeans are engaged in running (Melorose, Perroy, & Careas, 2015). One possible explanation would be that the requirements for training are only two: eagerness and sneakers. The willingness for practicing sports is an intrinsic factor. The choice of buying one or another type of shoe is not. Consumers' main focus are: first their colours, second their brand and third their cushioning (Branthwaite & Chockalingam, 2009). However, this research is oriented to really sporty people, leaving aside fashion and style aspects.

It is a true fact that people are influenced by their past experiences. We choose a brand because we were granted with a good performance by the same marque. We decide to buy the same shoes because the last pair have had a long durability. We are always comparing the comfort of the shoes with the ones worn before. Running pattern should not be an exception. We are heel-strike runners because it seems the most comfortable gait for us. But, does our body adapt the running pattern when the shoe weight increases? Does it make the same adjustments when this weight decreases? Are we aware of this variations or our brain just acts unconsciously? Which parameters are the main drivers for these changes?

In order to solve these complex inquiries, the project will evaluate key parameters of the running patterns. Measuring systems have evolved and currently we can benefit a lot from the reliability and accuracy of the information. The present study will be focused on the variation of the kinetic values with pressure insoles from Moticon and the fluctuation of some kinematic variables with the motion system Vicon Nexus.

In preliminary tests, a significant difference between the graduate increase and graduate decrease of the shoe's weight perception and movement pattern during running has been detected. The main aim of this project is to measure the influence of the perceived shoe weight on the kinematic and kinetic parameters. This is the departure point of this study.

2. Background

2.1. First Researches

The history of shoes starts a while back. First footwear was invented around 40,000 years ago and its functionality was to protect the sole from the rough surface. It was just before the end of the 19th century when shoes were first introduced into sports. Since then, the evolution of footwear technology has changed tremendously as well as the athlete's profile. In the 70's runners were only professional athletes and 75% of which, were males. Nowadays most of the runners are recreational who just practice this sport with the aim of being fit, and 54% of which are women (B. M. Nigg, Baltich, Hoerzer, & Enders, 2015).

Functional aspects have been studied and modified in order to gain the full satisfaction of customers. The best footwear aims to improve its comfort, performance, injury perception and durability (Sterzing, T., Lam, W. K., & Cheung, 2012). Moreover, comfort improves the runner's performance and it leads to reduce the likelihood of exercise-related injuries. It has been revealed that between a 37% and 56% of runners are injured every year.

Some researches state that these injuries could come from the usage of shoes in the practice of sports. This is the reason why major shoe manufacturers want to go back to the origins by reintroducing the natural shoe concept (Bruggemann, 2006; Lieberman, Davis, & Nigg, 2014). Brüggemann (Brüggemann, 2006) affirms that running shoes increase the risk of ankle sprains and *plantar fasciitis* by modifying the transfer of forces to the muscle and the body structure. Hence, athletes can reduce their risk of injury with natural shoes as they simulate barefoot running.

On the other hand, a lot of improvements and studies have been made with some variations of normal trainers. Unstable shoes were first introduced by Masai Barefoot Technology (MBT). Their constant instability was designed to train the small muscle units of the ankle joint and consequently improve the wearer's postural control. This leads to less knee and lower back pain when subjects wear regularly unstable shoes (Benno M. Nigg, Emery, & Hiemstra, 2006). Also, the centre of pressure (COP) excursions are greater while standing with the MBT technology shoes, compared to the normal ones as the body sways more to maintain the postural control (B. Nigg, Hintzen, & Ferber, 2006). In addition, some gender differences have been revealed in the study made by Nigg et al. (Benno M. Nigg, Tecante, Federolf, & Landry, 2010). The results suggest that women and men control their ankle joint using different strategies when walking or standing with this type of shoe. More specifically, females show larger COP excursions than male subjects.

In the field of performance, a lot of research has been done. Some investigations indicate that subjects with a good performance under one footwear condition tend to also perform well under other conditions (Waddington & Adams, 2003). Other suggest that the cushioning is a relevant factor to study. For this reason, the hardness of the shoe's insole has been determined as the main aspect of performance. It has been revealed that hard cushioned insoles reduce loading rates in the landing phase (Alirezaei Noghondar & Bressel, 2017). Therefore, better performance is expected as the plantar fatigue is reduced.

Finally, the comfort perception might be associated with physiological factors such as the subject's daily mood. To avoid this perturbation music should be played during the experiments. Bonnette et al. (Bonnette, Smith III, Spaniol, Ocker, & Melrose, 2012) suggested in their study that the music has a positive effect in running performance but not in the exertion. This influence will normalize the different runners' perceptions about their comfort and discomfort.

2.2. Studies for the Measure of Comfort and Discomfort

In order to understand the main drivers of performance and comfort, researches can be divided into analysis of subjective and objective parameters.

2.2.1. Subjective Studies

In the field of comfort measures, different methods of measuring the discomfort has been tested in order to determine their reliability such as VAS (Visual Analog Scale), Ranking scale, Likert scale and Yes-No questions (Hoerzer, Trudeau, Edwards, & Nigg, 2016; Mills, Blanch, & Vicenzino, 2010; A Mündermann & Nigg, 2001; Anne Mündermann, Nigg, Stefanyshyn, & Humble, 2002).

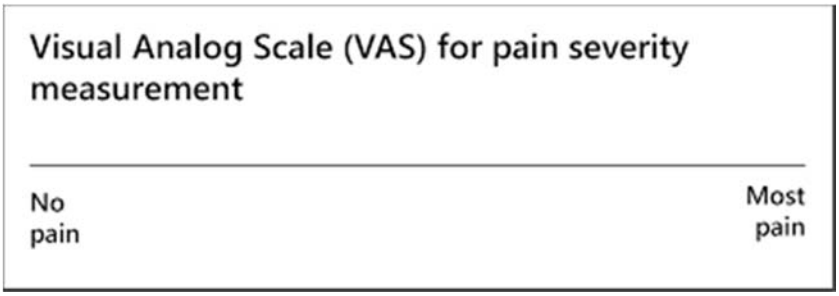


Figure 1 — Visual Analog Scale (VAS) 100 mm (The CHP Group, 2015)

The subjectivity of the shoe's comfort is undeniable. A footwear condition that is uncomfortable to one user may be comfortable to others. Even though, common preferred conditions such as little pain in the back and lower extremities have been identified (Müdermann, 2000). In addition, Mills et al. (Mills et al., 2010) noticed arch as the most important consideration in footwear comfort.

Moreover, comfort is always influenced by the comparison of features of the shoe that someone has worn before. Thus, Mündermann et al. (Anne Mündermann et al., 2002) concluded that the reliability of the measurements improved considerably by including a control condition to the tests. Also, she indicated the importance of shoe inserts on the overall comfort rating. She suggested that comfort rating was affected by the hardness of the insert material. Results showed that soft insoles were rated four points higher than the hard ones.

Going one step further, the comfort perception could vary between the testing sessions for the same shoe and the same subject (Hoerzer et al., 2016). Some researchers suggested that only the comfort ratings after two (Mills et al., 2010) or three sessions (Anne Mündermann et al., 2002) are reliable.

Hoerzer et al*.* (Hoerzer et al., 2016) studied the intra-rater reliability of footwear-comfort comparing two types of assessments: Yes-No questions and VAS (Visual Analogue Scales). He concluded that the Yes-No questions had a better reliability (47%) than the VAS (31%) but even so, both results were very weak. He suggested that this low reliability could be associated with the difficulty to control factors influencing the psychological conditions. This is why the study has to be carefully designed to maintain other mechanical factors constant, such as the speed of the treadmill.

In terms of utility, Yes-No questions provide a very simplistic answer which is an advantage when the objective is to determine whether a shoe is comfortable or not. On the other hand, VAS questionnaires deliver more precise and accurate information to analyse. VAS allows evaluating how much footwear conditions differ in comfort levels.

That's why, even though Mills et al. (Mills et al., 2010) concluded in their research that Ranking Scale is more consistent than the VAS measure, other researchers accept VAS as the most efficient and trusty way to extract subjective data. More precisely, those VAS that are 100-150 mm in length and delineate the extremes have been determined to have the greatest accuracy (Hoerzer et al., 2016; Mills et al., 2010; A Mündermann & Nigg, 2001; Anne Mündermann et al., 2002).

By using a VAS questionnaire an important parameter can be extracted. The minimal clinically important difference (MCID) is defined as a threshold above which outcome is experienced by the patient. This limit would be the smallest difference in a score that would change in perception from comfortable to neutral or from neutral to uncomfortable. Mills et al. (Mills et al., 2010) found out that using a 100-mm VAS a clinically important change in comfort was 9.59mm.

Owing to the nature of all the previous scales, it seems convenient to choose a mix of Yes-No and 100-mm VAS questionnaire.

2.2.2. Objective Studies

In the field of objective researches, Chen et al. (Chen, Nigg, & de Koning, 1994) studied the pressure distribution in order to measure the discomfort. They used four different types of shoe insoles combined with different comfort characteristics. The study suggests that while walking, higher forces and pressures were detected in the midsole area with the most comfortable insole. Whereas while running only the pressure of the medial forefoot was lower for the most comfortable insole. They found out unusual peak pressures in the medial forefoot and hallux when the shoes were uncomfortable. This suggested that a change in the pressure distribution could detect a change in the shoe comfort. For this reason, patterns of loading in the different foot regions should be analysed in our study, especially in the forefoot region.

Also, to prevent injuries, the interaction between diverse body characteristics has been reviewed. Mündermann et al. (Anne Mündermann et al., 2002) show in their study the importance of wearing a comfortable insole in order to avoid lower extremities' injuries. Excessive tibia rotation has been suggested as the main cause of knee injuries (Nurse & Nigg, 1999). Another parameter that has been studied is the interaction between three different types of court shoes and the β-angle (Miller, Nigg, Liu, Stefanyshyn, & Nurse, 2000). As measuring the β-angle (angle between the heel midline and the calf midline), participants with a low β-angle rated shoes more comfortable than those with a larger angle.

A more original study was developed about the different type of shoe-lacings (Fiedler, Stuijfzand, Harlaar, Dekker, & Beckerman, 2011). By using three lacing conditions (comfortable, loosened, and completely loose) they found out that the pressure time integral under the toes 2-5 and hallux increased 14.5% and 16.3% respectively. In addition, the in-shoe displacement increased. This led to an uncomfortable running experience as the forefoot region was overloaded. Finally, they noted an increasing walking speed when the shoelaces were loosened.

In the sensory field, the reaction of the body against temperature changes has also been studied. Nurse & Nigg (Nurse & Nigg, 2001) conclude in their research that "If sensory feedback is inhibited from a portion of the foot, the COP (centre of pressure) will shift the direction towards areas of greatest sensitivity during the stance phase of gait." This affirmation is crucial for diabetes patients who suffer from foot insensitivity. Thus, possible changes in their foot biomechanics might lead to deformities and increased pressure under metatarsal heads (Cavanagh, Simoneau, & Ulbrecht, 1993).

Nonetheless, not a lot has been researched on the matter of increasing and decreasing the shoe weight. It is clear that both, subjective and objective research, should be mixed in order to fully understand and forecast running patterns.

2.3. Studies on Shoe Weight

The evolution of running shoes has been tremendous in the last 100 years. New materials and technologies have transformed heavy shoes into lightweight and almost barefoot running footwear. Whereas some studies defend that the movement path does not change in different footwear conditions, other parameters have been reviewed to find evidence of the weight influence.

Several studies defend that performance can get worse as the weight of the shoe increases. It was shown by Flaherty (Flaherty, 1994) that wearing a shoe of 700g increased the oxygen consumption by a 4%, compared with running with bare feet. This higher consumption could be attributed to the additional mass or to the modification of the running pattern.

Divert et al. (Divert et al., 2008) have taken ahead a research using shocks loaded and comparing the results with shoes with the same weight in order to determine the answer. Their results showed a clear mass effect on the oxygen consumption. Nonetheless, the changing of the pattern movement did not determine the increase on the intake air.

It has implications not only in the sport field but also in the army, where a pair of boots weight between 1.7Kg and 2Kg (Osinski et al., 2004). A study was undertaken to determine if different types of insoles would attenuate the peak pressures during heel strike and forefoot loading inside military shoes (Windle, Gregory, & Dixon, 1999). The results showed that the usage of softer insoles yields a reduction of a 27% on the peak pressure at heel strike during running and a 23% reduction when marching. This implication makes a plantar pressure insole a perfect way to record data.

Previous studies of Martin (Martin, 1985), defended that adding less than 0.5kg of mass per foot does not lead to any significant modification in kinematic data during running. However, by increasing the weight, several studies revealed changes in the kinematic body parameters have been noticed. Chang-Soo et al. (Chang-Soo & Hee-Suk, 2004) found out that the Achilles tendon and initial rear-foot pronation angles were smaller with additional weight shoe compared to a barefoot condition. Also, the time of Max Vertical Ground Reaction Force of an additional weight was longer than when foot bared. Finally, higher peak pressures have been noticed in the medial region than in the lateral region when using heavier running shoes.

Taking injuries into consideration, only a few studies have compared different running shoes in relation to running injuries (B. M. Nigg et al., 2015). From the previous researches, it would be expected that lighter running shoes would avoid injuries. Nonetheless, Ryan et al. (Ryan, Elashi, Newsham-West, & Taunton, 2014) made the comparison between minimalist footwear and conventional neutral shoes. The results conclude that the injury frequency increases, with the minimalist shoes, about a 200%. Also, athletes in the minimalist condition reported greater calf and shin pain. These results are against the supporters of the minimal shoes. They have strong evidence that by wearing minimal shoes, runners will show a clear decrease of

Figure 2 — Minimalist shoe from Nike (Range, 2013)

lower extremity injuries (Bruggemann, 2006). By analysing the data with the Vicon system we will search for possible ankle or knee displacements that could predict injuries.

Discomfort also could be seen as the main driver of injuries. Runners intuitively choose comfortable shoes using their own comfort filter (B. M. Nigg et al., 2015). This may actually help them to run in the preferred movement path and thus, reduce the injury risk. Milani et al. (Milani, Hennig, & Lafortune, 1997) noticed a reduction of the first impact forces when subjects were running in stiffer shoes. The cautiousness of this action evidences that they adapt their running in order to avoid higher heel impacts and protect the body.

Athletes also make their selection influenced by their past experiences. That's the reason why it is so difficult to find the perfect shoe weight for the entire market segment. Individual body weight, incorrect foot alignment or malposition of the legs, are just a few examples of these personal differences. In addition, published research suggests that there is an alteration in the weight perception because of the poor sensory abilities of the foot (Slade, Greenya, Kliethermes, & Senchina, 2014). This experiment chose five different types of shoes with a different mass. Participants were asked to scale them from the lightest to the heaviest shoe, first weighted by their hands and then by their foot. This concludes that the upper extremities are more sensitive to low weight changes. Nonetheless, for extreme variations (approximately around 140g) the lower extremities are more precise. In order to find out the reaction of the body for both situations, this study will have weights below and above this threshold.

Taking all the previous studies into consideration, it has been demonstrated the relevance of the shoe weight in the comfort and injury fields. It is clear that there is a modification of kinematic parameters in a small or large scale. However, it is still not evident the origin of these changes. Type of shoes, fatigue, or only the proper perceptions might have a strong effect on the pattern movement and, therefore, on possible running-related injuries. In this study, it is speculated that there will be different body parameters and perceptions by first trying a neutral shoe and a weighted shoe and then carrying a heavy shoe and a neutral shoe.

2.4. Studies on Sensors

A lot of research has been done in the field of sensors and data collection. Nowadays, the instrumentation used is only for clinical applications as the systems are expensive for working on a larger scale (Simon, 2004). Not a lot of subjects can participate in the experiments, which is a big problem if the research goal and clinical use are rehabilitation, neurology or orthopaedic trauma, as for consistent results they should be tested in many more patients.

Moreover, some of the previous data collectors, such as pressures plates, were also highly specialized and difficult to interpret results of. Their gait analysis was limited to a certain indoor space and footsteps. In addition, conventional gait analysis only allows momentary views of the subject's performance. And lastly, the subject requires familiarization to make contact with the platform (MacWilliams & Armstrong, 2000).

As the recording methods need continuous data with long-term measuring capabilities, new systems try to solve these limitations. Plantar pressure insoles seem to be the ideal solution. They reveal the interface pressure between the shoe sole and the foot plantar surface. To design the desirable plantar pressure system the following target implementation requirements have to be fulfilled: it has to be light, wireless, flexible, cheap and low power consuming (Abdul Razak, Zayegh, Begg, & Wahab, 2012). In their review, Abdul Razak et al. (Abdul Razak et al., 2012) determine the main aspects that the sensors should have: low hysteresis, linearity, low-temperature sensitivity, pressure range until extreme measures of 3 MPa, area of sensor minimum 5x5 mm, operating frequency less than 200Hz, low creep and good repeatability. Once all the previous parameters are met, foot plantar pressure systems are the perfect tool to record gait data.

To complement this kinematic study, a lot of research has been done on the motion analysis. Motion capture is used in the fields of biomechanical, sport and animal science. Recent researches were designed to analyse the movement of pathologic gait for the treatment of children and adolescents with cerebral palsy (Davis et al., 2000). Davis et al. (Davis et al., 2000) began the documentation of standardized data collection protocols for clinical gait analysis. This lead to a major discuss of the reliability of the data collected.

Ferrari et al. (Ferrari et al., 2008) examined five protocols on the same gait cycle and they all revealed good intra-protocol repeatability. The importance of the conventions and definitions seem more crucial than the design of the market-set. In addition, Gorton et al. (Gorton, Hebert, & Gannotti, 2009) found out that with no standardization protocol, more than a 75% of the overall variance could not be attributed to the motion capture system. Thus, it is crucial to have a precise marker placement protocol in order to avoid the variability between examiners. Finally, they point out the importance of the calibration of the system and its configuration to reduce the overall variability.

For this reason, gait and motion analysis have been determined as powerful tools with a wide range of applications and optimal for our study.

2.4.1. Moticon

In order to analyse the first contact between body and shoe, insole plantar pressure analysis will provide a lot of interesting data such as the centre of pressure and its velocity (Abdul Razak et al., 2012). Moticon OpenGo is one of the best in-shoe foot plantar sensors for clinical and research trials and it allows to record data over a long period of time (Braun et al., 2015). The wireless OpenGo system makes a quick system application, analysis, and gives feedback under complex field conditions.

The insole weights no more than 80 grams and gives extra cushioning to the runners. This will lead to an attenuation of the peak pressures generated during heel strike and forefoot loading (Windle et al., 1999). Also, the top layer of the shoe is washable and thus, provides a sanitized scheme. It meets almost all the target implementation requirements for a foot plantar pressure insole: its weight is less than 300g; it is limited cabling; its sensors are thin, flexible and light; and it has a low power consumption (Abdul Razak et al., 2012).

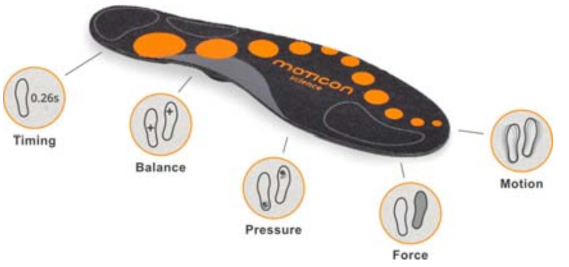


Figure 3 — Moticon OpenGo left insole (Range, 2013)

OpenGo system has two insoles with 13 capacitive sensors that cover 52% of the insole area. Each of them has a tri-axial accelerometer and a data storage chip that measures acceleration, plantar pressure distribution, peak pressures, motion sequences, gait patterns and temperature. It allows to record 5:48h at a sample rate of 50Hz and it can be connected by USB antenna to a computer running Moticon's Beaker 5 Software (Braun et al., 2015; Oerbekke et al., 2017; Stöggl & Martiner, 2017). Analysis with this Software is fully automatic: it generates gait, jump, static and balance reports.

In addition, many researches have been made in order to determine the validity and reliability of the data collected. Compared with stationary traditional systems, OpenGo has been defined as a feasible and reliable tool for clinical trials and gait analysis over a long period of time (Braun et al., 2015). Stöggl et al. (Stöggl & Martiner, 2017) also defend OpenGo usage for research and clinical settings in order to evaluate temporal, balance and force parameters. Its reliable source of data gives the researcher accurate results during walking, jumping, running, body balance and special imitation motions specific to cross-country skiing. Nonetheless, Oerbekke et al. (Oerbekke et al., 2017) only find OpenGo valid during walking. They have not considered valid the values for the centre of pressure during unilateral stance. Therefore, possible errors have to be considered in these measurements.

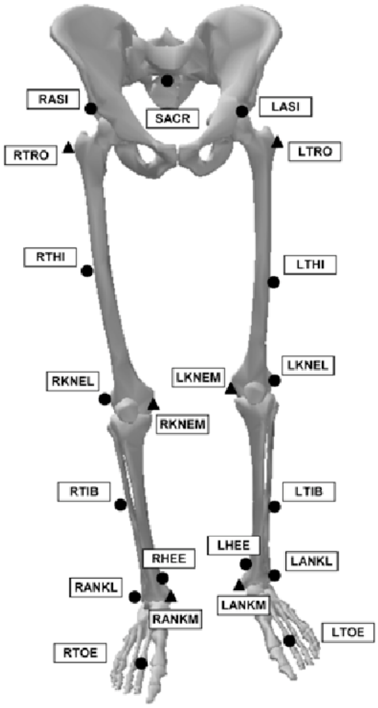
2.4.2. Motion Analysis

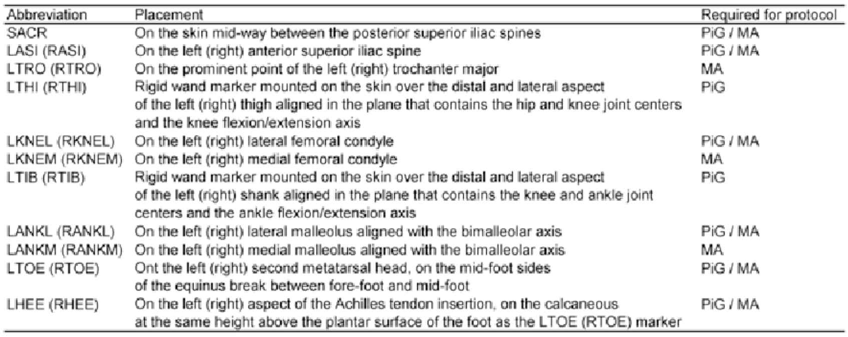
To complement this research, a motion analysis of lower extremities is needed. The instrumentation that will be used is an 8-camera system from the company VICON Motion Systems. Vicon uses a reflecting material in order to record the data. These reflectors are called markers and they are available at frequencies larger than hundred Hertz. The software used calculates joint movements within an arena for ground truth positioning, 3D reconstructions or real-time control.

As it has been commented on the previous sections, the marker's set position is relevant for recording the data. Protocols of gait analysis want to make kinetics and kinematics of pelvis and lower extremities interpretable (Sutherland, 2002, 2005). They also define the procedures for data collection, processing, analysis and reporting of the results (Ferrari et al., 2008).

Moreover, the importance of the marker location has been noticed in the studies of Chambers and Goode (Chambers & Goode, 1996). They have determined that more than 90% of the variability comes from the placement of the market set. For this reason, it is crucial to define properly the position of each marker to reduce the variability between examiners.

These markers have to be placed in a specific junction of the body and usually, the standard Plug-in-Gait (PiG) is utilized. Nonetheless, this protocol is prone to errors arising from inconsistent anatomical landmark identification and knee axis misalignment. Stief et al. (Stief, Böhm, Michel, Schwirtz, & Döderlein, 2013) have designed a custom-made protocol (MA) as a complement of the PiG that lowers measurement errors. This new protocol uses additional markers to determine joint centres. A total number of 21 retro-reflective markers will be placed on the surface of the skin or clothes as shown in *Figure 4.*





Abbreviation	Placement	Required for protocol
SACR	On the skin mid-way between the posterior superior iliac spines	PiG / MA
LASI (RASI)	On the left (right) anterior superior iliac spine	PiG / MA
LTRO (RTRO)	On the prominent point of the left (right) trochanter major	MA
LTHI (RTHI)	Rigid wand marker mounted on the skin over the distal and lateral aspect of the left (right) thigh aligned in the plane that contains the hip and knee joint centers and the knee flexion/extension axis	PiG
LKNEL (RKNEL)	On the left (right) lateral femoral condyle	PiG / MA
LKNEM (RKNEM)	On the left (right) medial femoral condyle	MA
LTIB (RTIB)	Rigid wand marker mounted on the skin over the distal and lateral aspect of the left (right) shank aligned in the plane that contains the knee and ankle joint centers and the ankle flexion/extension axis	PiG
LANKL (RANKL)	On the left (right) lateral malleolus aligned with the bimalleolar axis	PiG / MA
LANKM (RANKM)	On the left (right) medial malleolus aligned with the bimalleolar axis	MA
LTOE (RTOE)	Ont the left (right) second metatarsal head, on the mid-foot sides of the equinus break between fore-foot and mid-foot	PiG / MA
LHEE (RHEE)	On the left (right) aspect of the Achilles tendon insertion, on the calcaneous at the same height above the plantar surface of the foot as the LTOE (RTOE) marker	PiG / MA

Figure 4 — Marker set of both lower body protocols. The markers indicated by circles are part of the standard Plug-in-Gait (PiG) marker set; those indicated by triangles are the additional markers used in the custom made protocol (MA) (Stief et al., 2013)

Numerous studies have proven the reliability and accuracy of the Vicon Cameras. Barrows (Barrows, 2007) found a positioning error slightly larger than 1mm when using Vicon MX-F40 cameras in his wind tunnel experiments. This value is considered as a standard error for this type of systems. Afterwards, Manecy et al. (Manecy, Marchand, Ruffier, & Viollet, 2015) demonstrated that the position variability is less than 1.5mm. In more recent studies, Merriaux et al. (Merriaux, Dupuis, Boutteau, Vasseur, & Savatier, 2017) found in their static experiments a mean absolute error of 0.15 mm and a variability of 0.015mm. Confirming Vicon as an excellent precision system and high accuracy for static cases. In their dynamic experiments, the positioning error was lower than 2mm. In addition, they found out that the error is reduced by 40% if the object moves at higher speeds. Faster displacements lead to lower errors.

In the matter of markers, Yang et al. (Yang, Sanno, Brüggemann, & Rittweger, 2012) investigate four reflector sizes. They conclude that the marker size does not change the positioning performance. The most important parameter that could vary the accuracy is the Vicon camera sensor resolution. Merrieaux et al. (Merriaux et al., 2017) contradict this affirmation. They state that "the marker size and the Vicon sampling rate should be properly tuned with respect to the speed displacements encountered in the monitoring applications to reach the Vicon optimal performance". Finally, Diaz et al. (Novo et al., 2014) found out that motion capture perform also better when the cameras are closer to the tracked object.

All the previous researches reveal us the importance of a proper arena design for the experiments. Parameters such as marker placement, camera calibration, frequency of recording and speed of displacement have to be determined in order to get the right data.

2.5. Treadmill or Ground Running?

Several scientific studies have been done using a treadmill assuming that this simulates ground running. It is assumed that locomotion on a treadmill is similar to locomotion overground. However, there is no clear consensus about the extrapolation of these results. Whereas some researchers have found evidence of different running kinematic parameters (Dingwell, Cusumano, Cavanagh, & Sternad, 2001; Elliott & Blanksby, 1976; Mok, Lee, & Chung, 2009; Nelson, Dillman, Lagasse, & Bickett, 1972; Benno M. Nigg, De Boer, & Fisher, 1995; Sinclair et al., 2013), other argue that there are no relevant alterations of running patterns (Cunningham & Perry, 1995; Donoghue, Harrison, & Science, 2004; Lee & Hidler, 2008; Watt et al., 2010; White, Scurr, & Hedger, 2011).

In previous studies, Nelson et al. (Nelson et al., 1972) have found in their researches longer periods of support, smaller vertical velocity of the centre of mass and less variation in horizontal and vertical velocities of the centre of mass during treadmill. Elliott and Blanksby (Elliott & Blanksby, 1976) have been more precise affirming that at low speeds (3.3-4.8 m/s) subjects have the same shorter non-support period as well as a higher stride rate for treadmill.

In addition, Nigg et al. (Benno M. Nigg et al., 1995) have studied the landing style of 22 subjects, 8 of which have changed their running style from heel landing to midfoot landing in treadmill running. It is stated, that this reaction may be a consequence of a more stable perception from individuals. To reinforce this hypothesis, they have found a smaller shoe angle (angle between the shoe sole and the running surface from a lateral view, *Figure 5* ∂-angle) to increase the stability feeling when running on a treadmill.

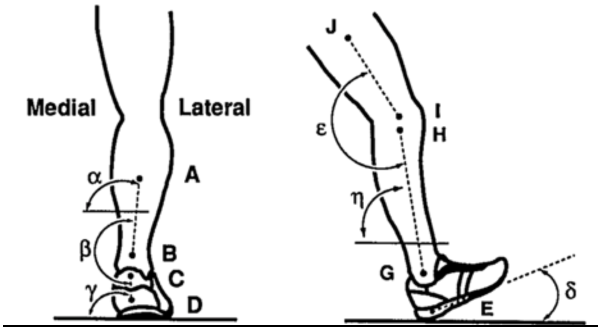


Figure 5 — Illustration of the most important angles from the lower extremities (Benno M. Nigg et al., 1995).

Also, more recent studies from Dingwell et al. (Dingwell et al., 2001) have demonstrated that treadmills can significantly alter the variability and local stability properties of locomotion and potentially lead to misleading conclusions.

To reinforce previous work, Mok et al. (Mok et al., 2009) have shown smaller stride length, stride time and stance time in the treadmill, attributing these changes to the backward drag force provided by the moving belt. They explain that this external force assisted the runner to complete the stance phase leading to decrease the stance time. Also, their subjects have changed their feet to a flatter position on the treadmill compared to overground. In addition, kinematic parameters in sagittal plane have been found significantly different between overground and treadmill running. They have found that the ankle angle at toe off decreased in treadmill.

Continuing with the kinematic parameters, Sinclair et al. (Sinclair et al., 2013) have noticed a significant reduction of the hip flexion at foot strike and ankle excursion to peak angle during treadmill running. Their studies have reinforced the wrong assumption of treadmill and over ground being equivalent environments to measure gait parameters. Therefore, they have advised about the poor treadmill's ability to mimic stance phase kinematics of over ground running during research.

To begin with the supporters of the treadmill reliable results, Cunningham and Perry (Cunningham & Perry, 1995) have found no significant differences in maximum rearfoot angles and have confirmed the accuracy of treadmill running while studying the rearfoot motion.

In further research, Donoghue et al. (Donoghue et al., 2004) have pointed out the importance of controlling speed as they have seen it as a critical factor in ensuring low variability between trials. Also, Watt et al. (Watt et al., 2010) have remarked that the maintenance of constant belt speed is crucial. The difficulty to measure and maintain a certain speed during many experiments is evident. This is one of the major advantages of using a treadmill for research. By using it, a very fluctuating variable can be eliminated and the correct conclusions can be drawn up.

Another advantage of the treadmill is that it enables the possibility to make a motion capture analysis with fixed and calibrated cameras. Watt et al. (Watt et al., 2010) have emphasized the importance of space and camera reduction when using a treadmill. It also allows a greater number of cycles to be captured as the subjects are running in a specific arena (Sinclair et al., 2013).

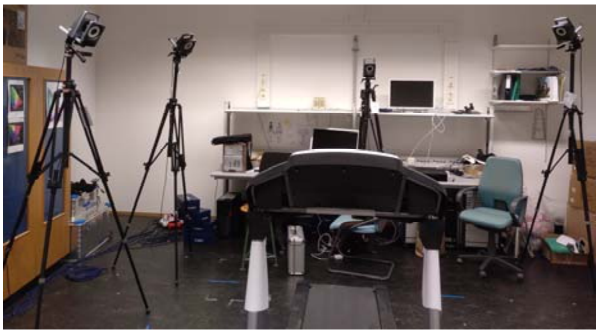


Figure 6 —Treadmill and Vicon camera's disposition for the experiment

Watt et al. (Watt et al., 2010) have analysed 22 kinematic parameters and 12 of them have been significantly different, but the magnitude of the difference has been comparable to the variability in normal gait parameters. For this reason, they have affirmed that treadmill gait mechanics are qualitatively and quantitatively similar to overground gait.

Finally, the study of White et al. (White et al., 2011) about the breast displacement across three breast support conditions, has shown similar stride frequencies and lengths in treadmill and over ground running. Moreover, the three-dimensional breast displacement and discomfort have not differed in the two running conditions.

Despite all the controversial arguments about the validity of treadmill results, lot of consensus have been arisen when affirming that experience with treadmill running is an important factor when studying biomechanics in this condition (Elliott & Blanksby, 1976; Benno M. Nigg et al., 1995; Sinclair et al., 2013; Watt et al., 2010; White et al., 2011).

For our study, several limitations have been taken into consideration: (1) the velocity has to be set constant at 10 km/h; (2) Vicon Nexus is a motion analysis system that records the date with fixed cameras; (3) The subjects have to run without any external perturbation such as discontinuities of the ground.

For this reason, the most suitable place to work has been a closed area with the help of a treadmill. More specifically, the treadmill used has been a Horizon Paragon 6 with a belt surface of 154 x 50 cm, velocity range of 0,8-20km/h, variable cushioning system (VCS) and built-in fan. These are the perfect conditions to emulate the normal gait during experimentation.

Figure 7 — Treadmill Paragon 6 used for tests

3. Hypotheses

3.1. Do the subjects change their running pattern when increasing the shoe weight?

To begin with the scientific study, it has to be defined whether the weight of the shoe influences the running parameters or not. From previous researches, some investigators defend this hypothesis (Chang-Soo & Hee-Suk, 2004; Turba, 2018) while others did not notice any change in the movement pattern (Martin, 1985; Benno M. Nigg et al., 2017). Our research has analysed several objective parameters with pressure insoles and motion analysis in order to define the running specifications correctly. The confirming or rejection of this hypothesis is crucial in order to predict athletes' inadequate movements or injuries.

3.2. Does the pressure distribution change when changing the weight?

On the previous study of Turba (Turba, 2018) a displacement of the COP has been noticed and the line gait seemed to start nearer to the heel. To solve this question, a proper study of the trajectory of the centre of pressure and its velocity has been carried out.

3.3. Does the peak force increase when increasing the shoe weight?

The peak force is one of the first parameters that have been studied. The action-reaction law says that when a body (the foot) exerts a force on a second body (the ground), the second body simultaneously exerts a force equal in magnitude and in opposite direction on the first body. Therefore, if the total weight is bigger, the reaction of the ground increases as well as the forces produced by our feet. For this reason, the fluctuations of the peak force when changing the shoe weight have been evaluated.

3.4. Is the swinging phase longer and contact time shorter when increasing the shoe weight?

Following the previous hypothesis, the swinging phase should be higher as volunteers will reduce high reaction ground forces with heavier shoes. It is known that athletes try to avoid excessive fatigue, for this reason they would have a shorter ground contact time and longer swinging phases.

3.5. Do the subjects change their knee angle when shoe weight increases?

More in detail, it is hypothesized that the weight of the shoe will change the knee angle while running. This hypothesis is against the normal pendulum simplification. The period of the double pendulum (the lower extremities) is not a function of the mass. So if the velocity of the treadmill is constant, also are the normal acceleration and the angle of the knee.

$$\tan(\varphi) = \frac{m \cdot a_n}{m \cdot g} = \frac{\frac{v^2}{R}}{g}$$

Symbol	Definition
φ	Knee angle [º]
m	Mass of the leg [kg]
a_n	Normal acceleration [m/s^2]
g	Gravity acceleration [m/s^2]
v	Linear velocity [m/s]
R	Leg length [m]

Table 1 — Definition of the variables used in the knee angle formula for a pendulum.

Nonetheless, it is suspected that the subjects will change their way of running in order to gain stability with heavier shoes.

3.6. Is the cadence modified when changing the shoe weight?

Another important parameter is the cadence of running. We would like to know whether the weight of the shoe has an influence on the number of steps fulfilled in a certain amount of time. With the help of Moticon and Vicon systems we will calculate the time between each peak of force and compare each shoe weight in order to find statistical differences in the cadence.

3.7. Is there any significant change between increasing and decreasing the shoe weight?

Furthermore, the main aim of this study has been to find differences between increasing and decreasing the shoe weight. It is hypothesized that people change their running pattern when they increase and decrease the weight even though the change value is the same. With this, we want to test the body memory and the influence of the shoes worn before. It is still not clear that changes made on the order of the shoes have an effect on the locomotion of the lower extremities.

This is the reason why this study has been divided into two phases: on the first part we have increased the weight from a neutral shoe to a heavier one and on the second part subjects have worn a weighted shoe in the first place and then a neutral shoe. By comparing the kinematic and kinetic parameters of the two phases we could answer the question to this hypothesis.

3.8. Do the subjects notice only weights greater than 150 grams?

Whereas the matter of the subjective study, this experiment has retested the conclusion which Turba (Turba, 2018) stated in their previous study “around 150g additional weight seemed to be the threshold of perception”.

3.9. Do perceptions affect the kinematic and kinetic parameters?

Finally, this thesis wants to answer the question whether the perceptions modify kinematic and kinetic parameters or not. If this hypothesis is true, a lot of injuries could be avoided. Professionals will acknowledge the changes on movement patterns based only on the perceptions of the athlete.

To answer this questions a combination of the objective and subjective data should be done and test the correlation between changes in the running patterns and perceptions.

4. Methodology

4.1. Test Preparation

As it has been defined in previous sections, the purpose of this study is to evaluate the relationship between perceptions and biomechanical factors when the shoe weight increases and decreases. The definition of the desired test protocol is a crucial step of the project. In addition, the determination of the control variables (time, speed…), independent variables (shoe weight) and dependent variable (COP, peak force…) will help us to extract the correct data and lead to reliable conclusions.

Firstly, shoe weight conditions have been established from previous tests in the research laboratory. Studies in the "Lerhstühl für Sports- und Materialengeräten" of the Technische Univesität München have found out a threshold of extra 150g (Turba, 2018) above which runners notice a clear increase on shoe weight. In order to retest this data, the combinations have been defined below this limit (50g), on the threshold (150g) and above it (315g).

It has been noticed, in preliminary tests, a significant difference between the graduate increase and graduate decrease of the shoe's weight perception and movement pattern in the gait cycle. For this reason, in our experimental procedure, subjects have to compare the control condition (N) with all of the shoe weight options (A, B and C). In order to save expenses, neutral running shoes (Victory Performance #1713301) from Deichmann have been purchased. Note that the control condition has a natural weight of 270 grams plus 80 grams from the insole (350 grams).

To test the hypothesis previously exposed, the experiment has been divided into two phases. In the first phase, the shoe weight increases from a neutral weight (N) to an extra mass (A: 50gram, B: 150g. and C: 315g.). In the next phase, the shoe weight decreases from an extra shoe mass (A, B and C) to a neutral weight (N). Also, a control condition (e.g. N-N) is included in both cases to validate the reliability of trials (Anne Mündermann et al., 2002). By randomizing the order within the two phases, we can measure the impact of the weight regardless possible memory perturbations. An identification number has been assigned (1-4) to each combination and the 'Randbetween' order from Microsoft Excel has been used.

The following Table 2 shows one possible experimental combination in a random order:

Increasing Weight	**N → A** Neutral shoe → 50gram extra	**N → N** Neutral shoe → Neutral shoe	**N → C** Neutral shoe → 315gram extra	**N→ B** Neutral shoe → 150gram extra	Total number of tests: 8
Decreasing weight	**C → N** 315gram extra → Neutral shoe	**A → N** 50gram extra → Neutral shoe	**N → N** Neutral shoe → Neutral shoe	**B→ N** 150gram extra → Neutral shoe	Total number of tests: 8

Table 2 — Example of a experimental combination in random order divided between increasing and decreasing the shoe weight.

Several alternatives for the increasing of shoe weight have been proposed. The first option has been modelling clay, but it has been discarded for its poor stickiness. To solve this, handball resin has been suggested. Nonetheless, its low density made it impossible to increase more than 300 grams without changing the shoe's balance distribution. Finally, high-density lead tape 2,54 cm width has been proposed as the best solution. Its durable stickiness and high density enables us to raise the shoe weight up to 315 grams avoiding perturbations on the running pattern. The lead has been simply stuck to the outside of the midsole, covering only the forefoot and around the heel. All the trainers, including the neutral one, have been covered with black tape in the lower part making it impossible to visually differentiate the weight.

Figure 8 — High-density lead tape used (Benno M. Nigg et al., 1995)

Figure 9 — Victory shoes used in the experiment. Left shoe is the control condition (N) and right weighted shoe of 315 grams (C). It is not possible to recognise visually the different weight.

Secondly, the duration of the experiment is an important control variable as it has to avoid subject's fatigue. Three minutes of warm up has been considered as an adequate time to get used to new running shoes. Then, the volunteers have to run for two minutes with every shoe weight combination (2 minutes x 16 combinations = 32 minutes). In order to eliminate fluctuations of the running speed, subjects run in a treadmill at a constant speed of 10 km/h (2,78 m/s). This is considered a light pace for a non-professional runner.

For the changing of trainers, insoles and answering the questionnaire it has been estimated that the subjects need 2 minutes per combination. This leads to a total duration of 1 hour and 9 minutes.

4.1.1. Volunteers

The main constrains for selecting a volunteer have been: shoe-size between 42 and 44, being an active-sporty person and no previous lower extremities surgeries. As a reward, snacks, beverages, a pair of socks and the opportunity to win a pair of running shoes has been offered to them.

An advert has been posted in the TUM University (see *Advertisement*) as well as in some sport centres. Nevertheless, not many responses have been received through this channel. Since the shoe-size for this experiment is a big limitation, many of the volunteers have been rejected, including girls. The vast majority of the subjects have been recruited for these tests thanks to the word of mouth.

It is a true fact that perceptions are affected by the subject's mood. In order to avoid this perturbation in the subjective and objective research, they have been asked for their favourite music playlist, which has been played during the whole experiment. A positive effect in running performance has been expected as Bonnette et al. suggested (Bonnette et al., 2012).

Instructions have been explained to each subject separately to eliminate differences in assessments between subjects resulting from inconsistent instructions.

4.1.2. Questionnaire

In order to collect the objective data, a questionnaire has been created. "QuestionPro Survey Software" has given us the opportunity to use this Pro version for free as the TUM University is currently participating in their Academic Sponsorship Program. By using this software, we have been able to make the answering process faster and given the subjects the possibility to change their answer if they made a mistake. Also, the practicability of extracting reports in an organized way is a positive aspect for working with QuestionPro.

According to the literature exposed in the previous sections, the Visual Analog Scale (VAS) of 100mm is the best tool to measure perceptions from runners (Hoerzer et al., 2016; Mills et al., 2010; A Mündermann & Nigg, 2001; Anne Mündermann et al., 2002). For this reason, the limiting condition has been the availability of this type of question in the questionnaire. In the “basic options”, the option "Text Slider", which is the most similar to VAS, can be chosen. By zooming in the screen, the questionnaire has been adapted to the correct 100mm size.

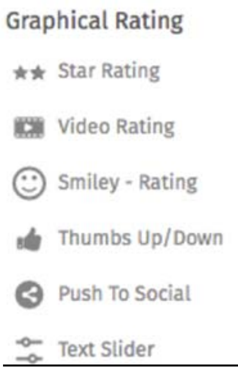
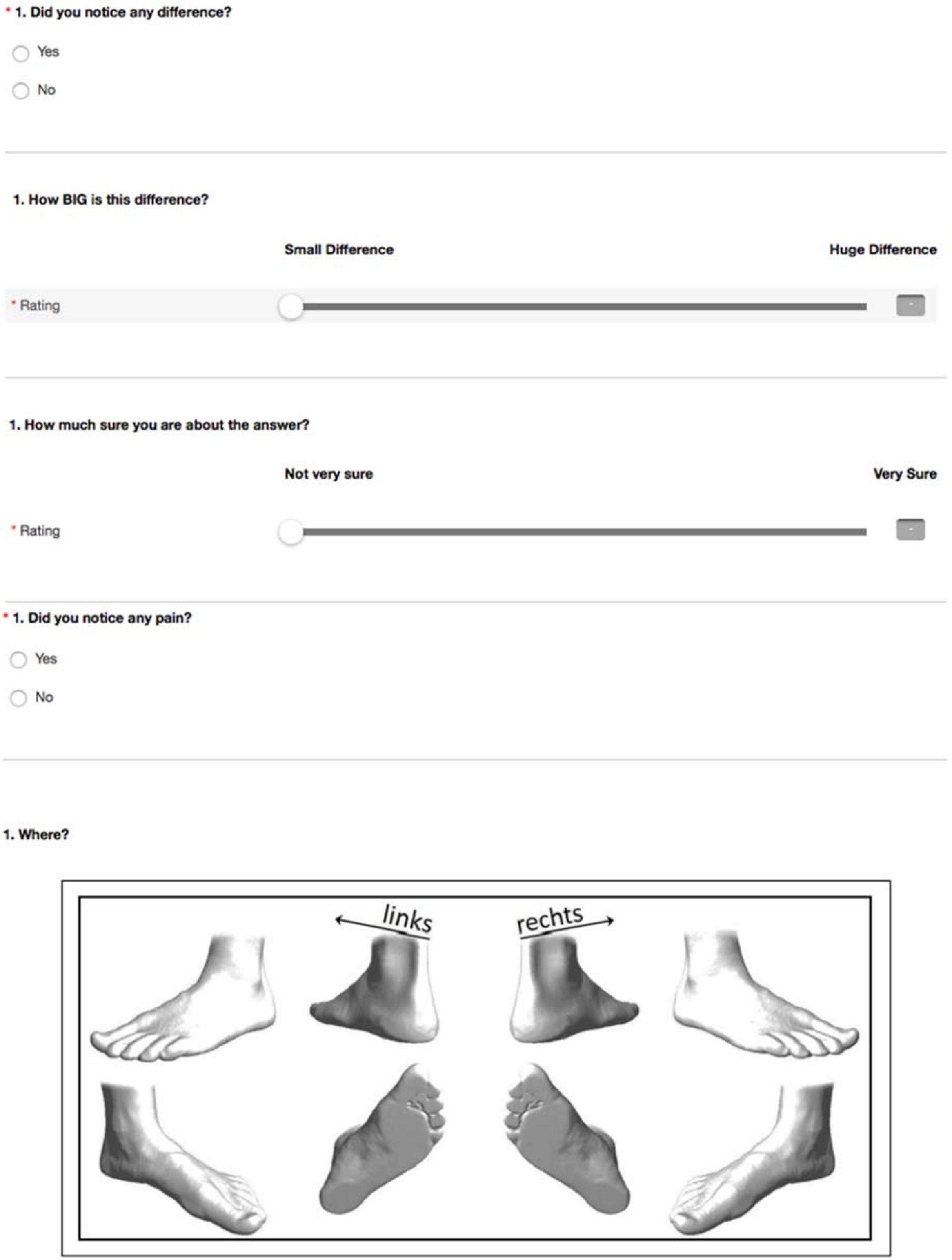


Figure 10 — Possible question options to use in Question Pro.

Once the Software has been defined, all the multiple features from there have been studied to make the most of this tool. An opening contact information survey has been created to gather the most relevant data of the user: name, e-mail, phone, age, weight, height and shoe size. After that, by a multiple-choice questions system, it has been possible to learn about their training frequency and previous injuries.

In the core of the survey, the subject has answered five simple questions once every two tested shoes. The main goal has been to compare the weight condition after running two minutes with the neutral shoe and two minutes with a heavy shoe (A, B or C) for the first phase. As it has been exposed in the *Section 2.2.1*, a combination of Yes/No and VAS questions have been proposed. The *Figure 11 and Questionnaire* shows the questionnaire that has been asked 8 times to each participant:



* 1. Did you notice any difference?

○ Yes

○ No

1. How BIG is this difference?

Small Difference — Huge Difference

* Rating

1. How much sure you are about the answer?

Not very sure — Very Sure

* Rating

* 1. Did you notice any pain?

○ Yes

○ No

1. Where?

Figure 11 — Extract of the questionnaire asked every two trials.

Finally, a last multiple choice question has been added asking the subject for his strongest leg. The reason for leaving this section to the end of the test has been to avoid changes on the pattern movement.

4.1.3. Objective Data

The objective data has been recorded with three systems: Moticon OpenGo, Vicon Nexus 1.8.5 and Garmin Forerunner 920XT smartwatch.

As it has been explained in the previous section 2.4.1, OpenGo is a plantar pressure insole which gives information about the pressures of 13 zones of the foot. The effect of increasing the shoe mass with Moticon insoles has been neglected as all the tests have been run with the same extra 80 grams weight.

Some considerations have been taken into account about the handling of the insoles during the experimentation. Firstly, the batteries have been charged after every session of testing to avoid the interruption of the data collection. Secondly, every two minutes of running the insoles have been changed from one shoe to the other. For making this transition correctly, the subject cannot remove them. Instead, the researcher has to replace them rapid and carefully. This is important as the durability of the sensors is severely reduced with too much insole bending. Finally, after downloading and saving the information recorded, the memory of the data storage chip has been cleaned to have enough space for the next tests.

Figure 12 — Right way of introducing the Moticon insole.

From the raw data provided by the software Beaker 5, the most relevant dependent variables that have been studied are the following: average of peak forces, time between peak forces, duration of the swinging phase, contact time, mean pressure of every sensor, mean pressure on the forefoot, mean pressure on the rearfoot, displacement of COP and velocity of COP.

On the other hand, Vicon Nexus has measured the trajectories of 21 reflectors attached to the subject's lower extremities. These data have been helpful to define the kinematic parameters. However, previous settings have to be done in order to get the right implications.

Figure 13 — Vicon Camera MX T10

The positioning of the 8 cameras (5 MX T10 and 3 MX T10-S) has been made in a certain way that the total treadmill and subject arena are covered. Moreover, the reflections coming from the treadmill lateral shining-grey-stripes have been removed with black paper. Also, the interaction with the blue light coming from other cameras has been avoided by their strategic placement.

Once all the cameras have been placed, they have been correctly calibrated with the T-Band. The calibration method consists in recording 3000 times the trajectory of one reflector from the T-Band for all the cameras at 50Hz. To ensure that high-quality kinematic data have been obtained, only calibrations producing average residuals of <0.3 mm for each camera and points above 3000 in all cameras were accepted prior to data collection. Afterwards, by setting the origin in the middle of the treadmill, the Software recognises the relative position of each camera. The calibration of the Vicon system was performed before each data collection session.

Further on, the subject definition has been made only once before all the experimental process has started. A ten second recording of the volunteer, with the 21 reflectors attached to his body, has been sufficient to define the model. In the *Section 5.2* the user will find more detailed information for using Vicon.

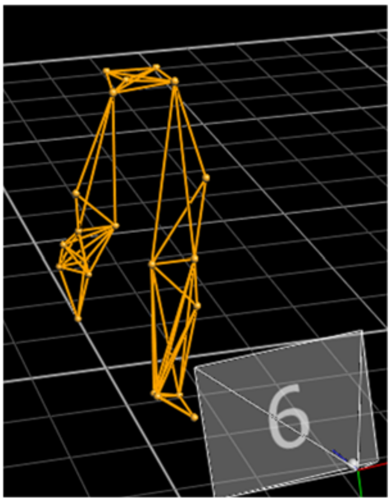


Figure 14 — Model defined with the 21 reflectors attached

Then, the gluing of the reflector has played an important role. It has not been able to use a full black costume, as this would make the runner sweat heavily. To solve this problem, two different types of tapes have been used. The first contact with the skin and clothes has been kinesiology tape as it lasts longer with the perspiration of the body. The second layer has been made with a double side tape to place the reflectors as Stief et al. (Stief et al., 2013) have proposed in their custom-made protocol.

In the first three minutes of warm-up, it has been checked whether the subject is sweating or not. If he has previously indicated that he usually sweats a lot, it has been decided not to record the data with Vicon. It has been observed that the user changed his pattern of movement when he noticed a poor stickiness of the tape, especially in the knees. Due to this distraction, he could fall on the treadmill and get injured during the experiment.

Finally, from Vicon Nexus 1.8.5 software, the most relevant dependent variables that have been studied are the following: maximal knee flexion angle during stance phase, maximal knee flexion angle during swinging phase and time between each peaks.

To measure the fatigue, the heart rate frequency has been recorded with a Garmin Forerunner 920XT smartwatch and read manually at the end of each run. This dependent variable has given a valuable information to the study, as the exertion of individuals could be tested by changing the shoe-weight.

4.1.4. Definition of Variables

The most relevant variables have been explained in the previous sections in order to define the experimental method. This section exposes a brief summary of such variables' definition:

Variable	Type	Explanation	Possible values	Unity
Shoe extra weight	Independent Variable	Extra mass added to the shoes with lead tape	$M \in \{0, 50, 150, 315\}$	[gram]
Speed of running	Control Variable	Speed constant of the treadmill	$V \in \{2.78\}$	[m/s]
Time duration	Control Variable	Time duration for every trial	$T \in \{120\}$	[seconds]
Warm-up duration	Control Variable	Time duration for warm-up	$W \in \{180\}$	[seconds]
Shoe size	Control Variable	Shoe size from the subjects	$S \in \mathbb{N}$ [42, 44]	[ ]
Perception on changing weight	Dependent Variable	How do the subject notice the weight difference	$P \in \mathbb{N}$ [0,100]	[mm]
Confidence in response	Dependent Variable	How sure are the subject about his answer	$C \in \mathbb{N}$ [0,100]	[mm]
Average of peak forces	Dependent Variable	Average of the Peak Forces in the stationary state	$F \in \mathbb{R}^+$	[N]
Time between peak forces	Dependent Variable	Duration of the cycles	$T_{PF} \in \mathbb{R}^+$	[seconds]
Duration of the swinging phase	Dependent Variable	Time duration when the foot is not in contact with the treadmill	$T_{SP} \in \mathbb{R}^+$	[seconds]
Contact time	Dependent Variable	Time duration when the foot is in contact with the treadmill	$T_{CT} \in \mathbb{R}^+$	[seconds]
Pressure on each sensor	Dependent Variable	Mean Pressure of every sensor	$P_i \in \mathbb{R}^+$ i = [1, …,13]	[$\frac{N}{mm^2}$]
Pressure on the forefoot	Dependent Variable	Mean Pressure of the 7 Moticon sensors placed in the forefoot	$P_F \in \mathbb{R}^+$	[$\frac{N}{mm^2}$]
Pressure on the rearfoot	Dependent Variable	Pressure of the 6 Moticon sensors placed in the rearfoot	$P_R \in \mathbb{R}^+$	[$\frac{N}{mm^2}$]
Average of the COP Displacement	Dependent Variable	Total sum of the COP trajectories divided by the number of steps in the stationary state	$D_{COP} \in \mathbb{R}^+$	[mm]
Average of the COP Velocity	Dependent Variable	Average of COP displacement divided by the average of contact time	$V_{COP} \in \mathbb{R}^+$	[mm/s]
Heart rate frequency	Dependent Variable	Heart rate frequency after two minutes of running. Recorded 16 times for each participant	$HR \in \mathbb{R}^+$	[bpm]
Maximal knee flexion angle during stance	Dependent Variable	Average of the maximal knee angle during stance phase in stationary state	$\beta_{ST} \in \mathbb{R}^+$	[º]
Maximal knee flexion angle during swinging	Dependent Variable	Average of the maximal knee angle during swinging phase in stationary state	$\beta_{SW} \in \mathbb{R}^+$	[º]
Time between maximal angles	Dependent Variable	Average Time duration between two maximal β_{ST} and β_{SW}	$T_{ST} \in \mathbb{R}^+$	[s]

Table 3 — Definition and explanation of each test variable

4.2. Study Protocol

This section has been created in order to understand the test protocol of the project. It is really important to have a clear procedure in order to reduce the experimental errors. In addition, this section intends to define the special working conditions to enable possible further research.

As it has been explained in the *Section 4.1.1*, a total number of 25 volunteers have been screened. Nonetheless, 7 of them have not been able to pursue the test as they had been previously injured or their shoe size was not available. Finally, a total amount of 18 volunteers have been tested with the following procedure.

Firstly, all the instrumentation and software have been prepared as follows. For Vicon System, the 8 cameras have been calibrated with the T-Band and the origin has been set in the middle of the treadmill. With the Moticon insoles, they have been linked with the software and the sensors have been zeroed. This procedure consists on lifting one leg to define the zero pressure for each participant. After having the insoles connected and ready, a Garmin Heart Rate band has been placed as well as the 21 reflectors like Stief et al. (Stief et al., 2013) proposed in their custom-made protocol (see *Figures 15 and 16*).

Figure 15 — Lateral view of one subject with reflectors

Figure 16 — Rear view of one subject with reflectors

Afterwards, individuals have been informed about the testing procedure and they have signed the document of compliance about being part of the experiment. After filling in the first part of the questionnaire, explained in the *Section 4.1.2*, the preferred subject’s playlist has been turned on.

The experimental test has started with a short warm-up of three minutes with the control condition (N) at 10 km/h. Once the participant has finished, the researcher has checked the condition of every reflector and he has considered the viability of recording the data with Vicon. If the subject suffers of abundant transpiration, markers have been unstuck to avoid their detachment in the middle of the experiment and possible injures induction. To sum up, if the individuals have a “high sweating rate” they only have used Moticon to gather the objective data.

As it has been explained in the previous sections, the experiment consists on running 2 minutes 16 times at 10 km/h on two phases. The first eight have been done increasing the shoe weight from the control condition to a weighted one (N→A, N→B, N→C). Also, the control condition has been added to validate the reliability of the measures (N→N). Keep the reader in mind that these four combinations have been tested in a randomized order. The second experimental phase has been done in the opposite direction. First, a weighted shoe has been worn and then the neutral one (A→N, B→N, C→N). As well as in the first phase, a control condition has been inserted and a random order between combinations has been kept. At the end of every two minutes the heart rate has been written down. In addition, after two tests, individuals have answered the perception questions. The subject has been always allowed to have a small rest between the transitions and the possibility to eat a snack or drink a beverage has been offered.

After finishing the exercise part, volunteers have terminated the questionnaire about their strongest lower extremity. This has been done by making them close their eyes and pushing them slightly from behind. The body reacts supporting its weight with the strongest leg.

Altogether, the total experiment has been done in about 1 hour and 9 minutes. Avoiding, this way, an extreme fatigue as individuals have been running 32 minutes overall.

The following flowchart enables the reader to understand the most relevant steps of the experimental procedure:

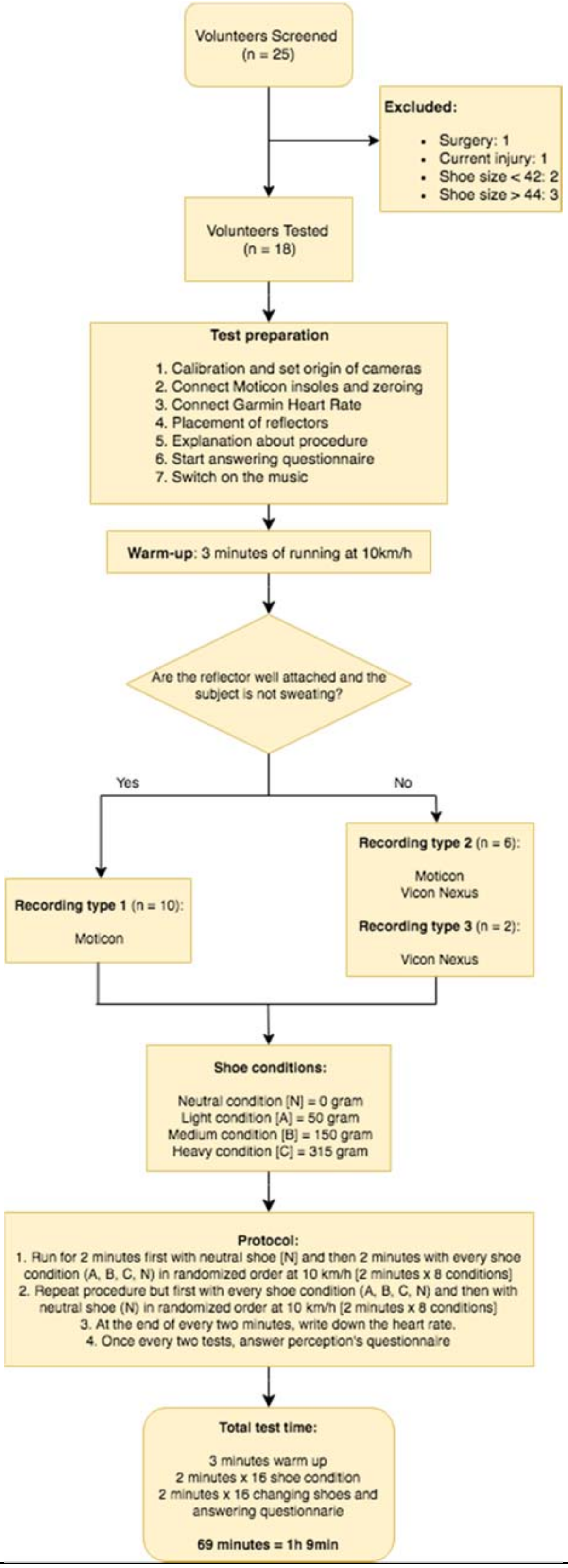


Figure 15 — Study protocol done with the Software Draw.io

5. Experimentation Clarifications

The main reason for the development of this section is to clarify the mistakes and adversities that the experimental procedure has faced. Also, to enable future researches, making the tests, with a better and faster guide through the settings. As it has been done through the whole thesis, we are going to divide the explanation by the two main systems used to record the data: Moticon and Vicon.

5.1. Moticon Problems

The data collected by Moticon has been very useful for this project. The possibility to record during a large amount of time without connecting the insoles, has allowed us to perform the trials without interruptions. However, this advantage is a double-edged sword as the researcher only knows the quality of the data at the end of the whole experiment. More specifically, we had problems with seven of our subjects.

In one of the tests, the batteries of both insoles lost their power supply and only the first phase was recorded. This was solved by using only full charged batteries. In 5 other tests, we saw that the right insole for the 42-43 size shoe had a lower force than the left insole and its data behaviour was unstable. This is the reason why this experiment has been relied mainly on the left foot. Lastly, we lost the whole test of one of the subjects due to a failure when reconnecting the insoles. As we couldn't afford to lose more data, we decided to visit the technical service and repair both insoles. To sum up, we lost the whole data from two subjects and we managed to get most of the information of five other volunteers.

Once all the data had been extracted from the insoles, it was decided to work with the raw data, as it was not clear the reliability of the damaged sensors. Self-customized formulas were created in order to identify: step detection, pressure distribution, centre of pressure's trajectories and velocities. By doing this, we realized how difficult is to create the Beaker 5 Software and the extraordinary work done by the Moticon's team.

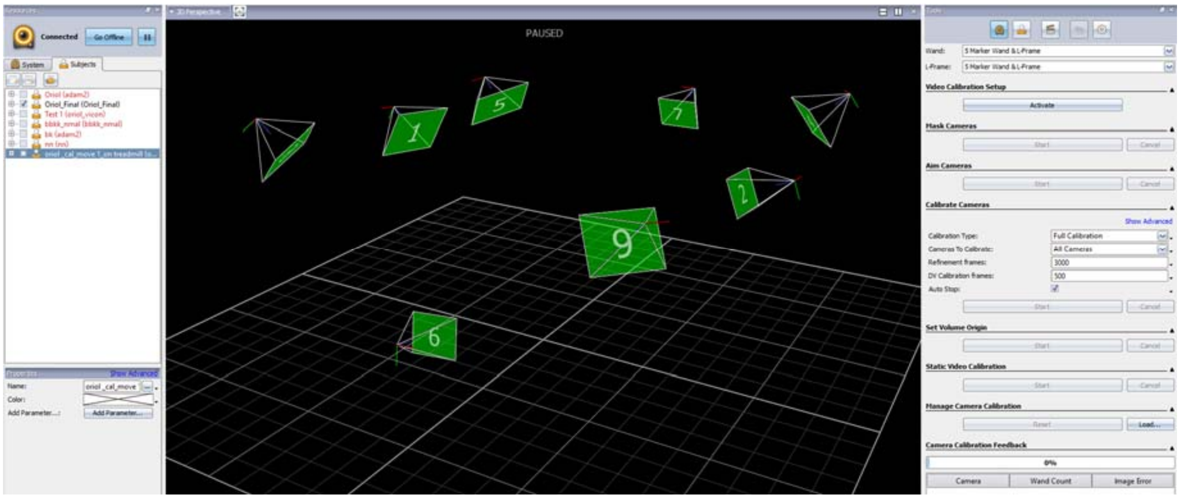
We suggested the company to add a battery level item in the interface, in order to avoid the interruption of the recordings. From our experience, we would recommend to check the data after every trial and give feedback to the company about the performance. They are always open to new inputs, as Moticon is making a big effort on improving the system every day.

5.2. Vicon Fast User Guide

This project has faced problems with the optimization of the Vicon system. It has not been possible to find a fast tutorial that helped us from the beginning of recording until having the data extracted. For this reason, this section has been created as a fast user guide, which will also show the difficulties while recording.

To begin with, the mouse clicks work different as in CAD software: right button to zoom in and out, left to rotate the arena and the rolling ball to move frame by frame.

Once the Software Vicon Nexus is opened and the cameras are connected with the button "Go live", proceed to calibration tab, press "System preparation → Video Calibration Setup → Activate → Calibrate Cameras → Start" (*Figure 18*).

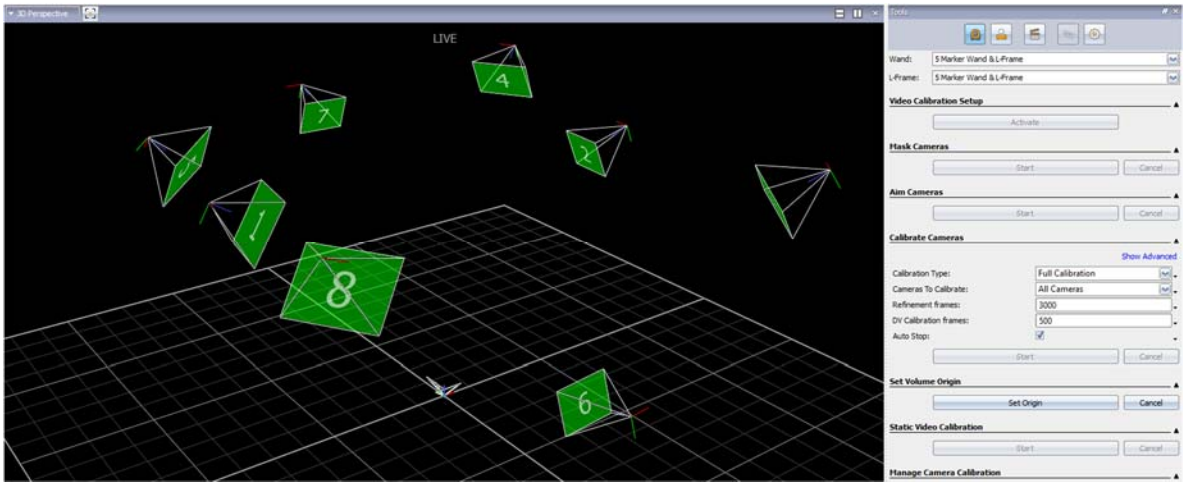


Wand: 5 Marker Wand & L-Frame
L-Frame: 5 Marker Wand & L-Frame
Calibration Type: Full Calibration
Cameras To Calibrate: All Cameras
Refinement frames: 3000
DV Calibration frames: 500
Auto Stop: ☑
Name: oriol_cal_move

Figure 16 — On the upper left side of the screen, press the button "*Go Live*". On the right side of the interface it can be seen the calibration options

By moving the T-Band with the 5 reflectors in circles, the software gets calibrated after recording 3000 times the trajectory of the T-Band. The user sees the evolution of this process by looking at the blue dot from the cameras: the faster this blue led blinks the better calibrated is the camera. Once all the cameras stop blinking, the software starts calculating the trajectories' error for each camera. If all of them have an error lower of 0.3 mm the calibration process is correct. Our suggestion is to hide all possible reflecting elements in order to have a fast and right calibration procedure.

To set the origin, place the T-Band in the middle of the arena. In the same tab, push the button "Set Volume Origin → Start", change the view option to "3D perspective" and select the T-Band as showed in the *Figure 19*.



Wand: 5 Marker Wand & L-Frame
L-Frame: 5 Marker Wand & L-Frame

Calibration Type: Full Calibration
Cameras To Calibrate: All Cameras
Refinement frames: 3000
DV Calibration frames: 500
Auto Stop: ☑

Figure 17 — On the top-left of the screen change to "3-D Perspective". On the calibration options "Set Origin".

Then, the user has to place the reflectors in the position defined on the volunteer and record a short sequence in a standstill position, where all the reflectors can be seen. The recording should be done in tab “Capture” on the selected folder (see *Figure 20*. Press “Start” and “Cancel” once the short trial is finished. In the option's view “Camera” the images taken by each camera may be seen. By pressing F2 the trial can be loaded again.

Trial Type: orriol_hidden partt

Session: Test 1\Session 1

Trial Name: Oriol_Final

Description:

Notes:

☑ Auto increment trial number

☑ Permit overwrite of existing files

Frames Captured: 0 0:00:00(00)

Figure 18 — In the capture settings define the name and folder. Then, start recording.

Once the test is loaded, go to “Subject Preparation → Subject Calibration → Fit Subject Motion” and click the “Core Processing” box and wait until it is finished (*Figure 21*). Now it's time to define the parts of the lower extremities. Select the “3D perspective”. In the tab “Subject preparation”, “Labeling Template Builder → Create Segments” write the name of the first part (e.g. hip) and click “Add Marker”. Then, connect the dots always selecting the furthest one. Once the segment is done, click “Create”.

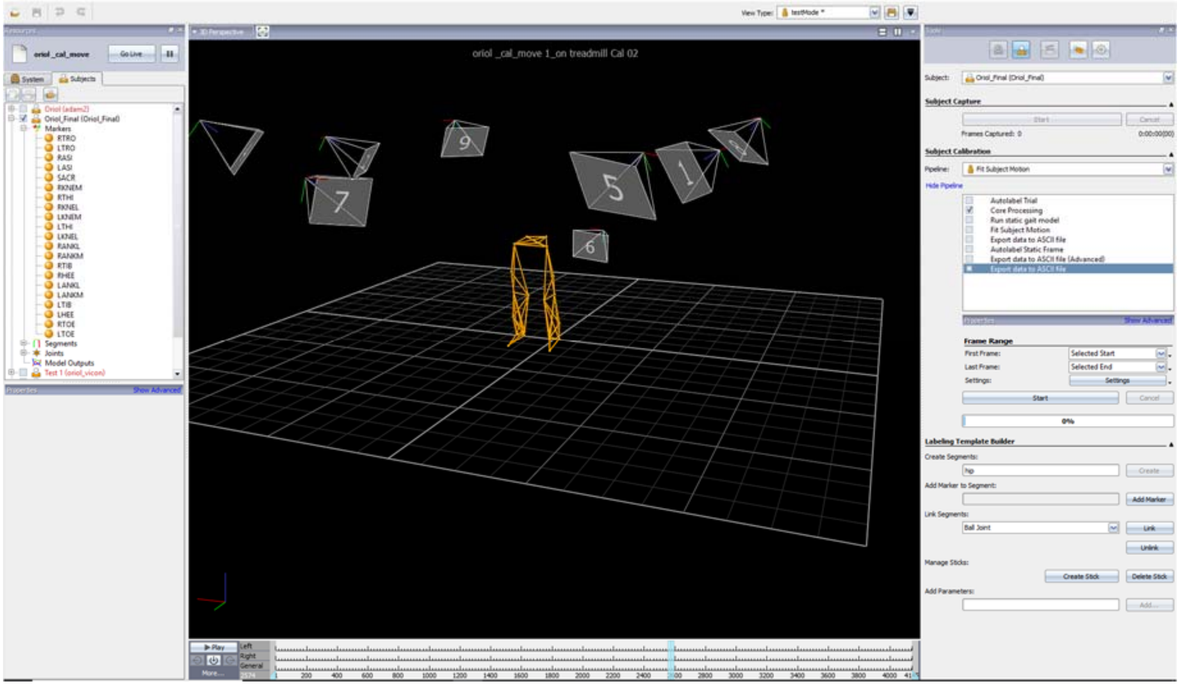


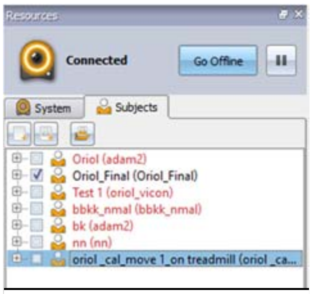
Figure 19 — On the right side of the interface “Core processing” and “Create segments”. On the left side we can rename the reflectors by double-clicking in the name of the markers.

In “Resources” the name of every dot can be defined (*see Figure 21*). Coming back to “Subject Preparation”, select "create link" taking in consideration all the possible link options: ball joint, free joint, hardly spicer joint, hinge joint and slider joint. In our case, for the link between the hip and upper-leg it a ball joint has been used, for the upper-leg and lower-leg (knee) link, a hinge joint and for the lower leg with foot (ankle) a free joint. Press “link” and select as a “parent segment” the hip and as a “child segment” the upper left leg, and repeat the process for the right leg. Repeat the process for the knee and ankle but changing the type of link. Be aware that this procedure has been made in only one frame, do not move the mouse rolling ball. Once all the links are defined uncheck “Core Processing” and check “Run static gait model” and then “Fit Subject Motion”.

In the resources part, click the right button of the mouse and “Save model as Template” in order to have the pre-setting saved.

Then, the recording procedure can be started. Remember to calibrate and define the origin every trial day. Go to the setting box and select the “Capture” icon. Now the folder and the name of the trial can be changed and you may start recording with the “Start” button. Change the name of the test every experiment in order to not replace older tests.

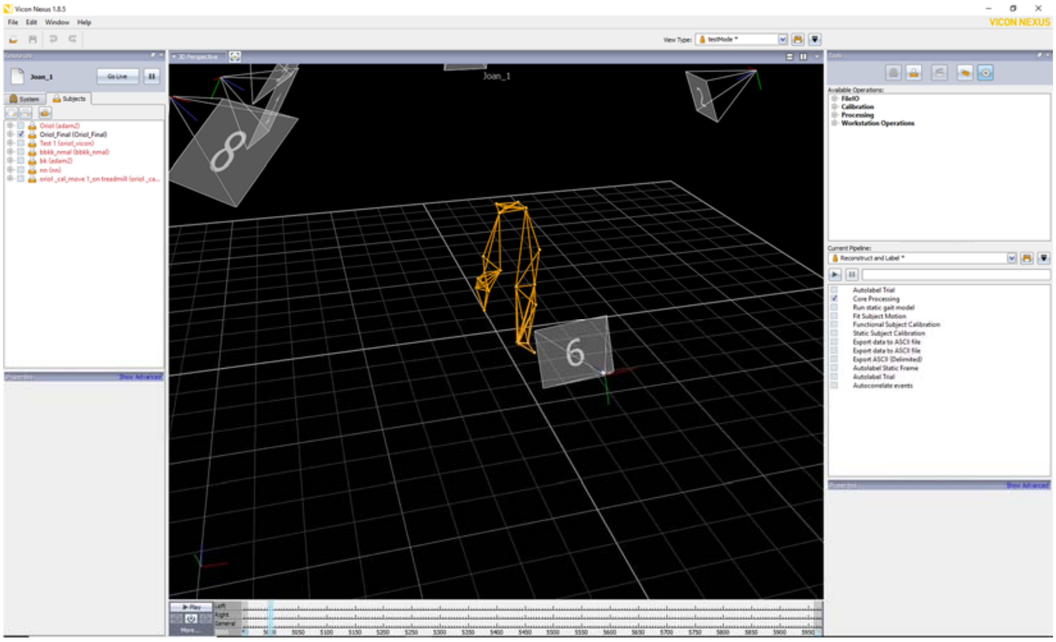
To process the data, go the “Pipeline” icon and load the test that you want to analyse. In order to avoid an excessive workload of the computer, it is highly recommended to switch off the hardware with all the cameras. Firstly, check the subject defined and uncheck the other in “Resources → Subjects”.



☐ Oriol (adam2)
☑ Oriol_Final (Oriol_Final)
☐ Test 1 (oriol_vicon)
☐ bbkk_nmal (bbkk_nmal)
☐ bk (adam2)
☐ nn (nn)
☐ oriol _cal_move 1_on treadmill (oriol _ca...

Figure 20 — Check the subject model and uncheck the others

Secondly, select the number of frames to work with from the lower part of the interface, including and extra margin of frames. Note that for processing 2 minutes of data it takes more than 15 minutes. In our study, it has been decided to analyse 10 seconds from the stationary state. Then, select the icon “Pipeline”, check the “Core processing” box and press play. Wait until all the frames are reconstructed in the “3D perspective” (see *Figure 23*).



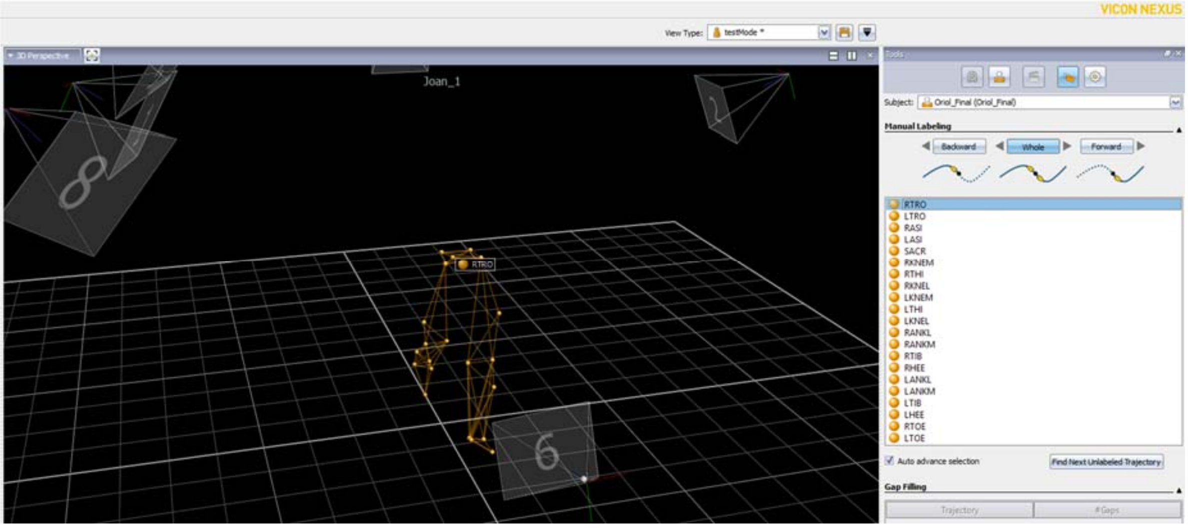
☐ Oriol (adam2)
☑ Oriol_Final (Oriol_Final)
☐ Test 1 (oriol_vicon)
☐ bbkk_nmal (bbkk_nmal)
☐ bk (adam2)
☐ nn (nn)
☐ oriol _cal_move 1_on treadmill (oriol _ca...

Current Pipeline: Reconstruct and Label *

☐ Autolabel Trial
☑ Core Processing
☐ Run static gait model
☐ Fit Subject Motion
☐ Functional Subject Calibration
☐ Static Subject Calibration
☐ Export data to ASCII file
☐ Export data to ASCII file
☐ Export ASCII (Delimited)
☐ Autolabel Static Frame
☐ Autolabel Trial
☐ Autocorrelate events

Figure 21 — First define the number of frames to analyse. Then check "Core Processing" and press "Play"

Almost in all the experiments, the labelling is not done properly. That's why every frame has to be checked to see if all the reflectors correspond to every marker previously defined. To do this, go to the first frame and select the icon "Label/Edit". For this frame select "Manual Labeling → Whole" and define every dot with its corresponding name. Then, select "Forward" and check that all the markers are settled on a part of the lower extremities. To delete a wrong selection, click the right button of the mouse a choose "Delete Section And Unlabel Forwards". Check that from this frame until the end of this marker is unselected. To label again, select the desired dot with the correct name (see *Figure 24*).



View Type: testMode *

Subject: Oriol_Final (Oriol_Final)

☑ Auto advance selection

Figure 22 — Process of Manual Labeling and example of relabel the reflector RTRO

On the last full frame, verify that all reflectors are in the screen and well connected. If some are left, move to forward frames until you find those reflectors. Then recheck visually the sequence and correct the mistakes.

From frame to frame sometimes the cameras don’t recognize the reflector and lose the trajectories. For this reason, the software permits to fill in these gaps with two types of lines: “Spline Fill” or “Pattern Fill”. The first option is useful when there is no other reflector reference that makes almost the same trajectory. It is recommended to use “Pattern Fill” when you have, for example, the symmetric reflector in your body, then choose this reflector by clicking on “Pick Source” (*see Figure 25*).

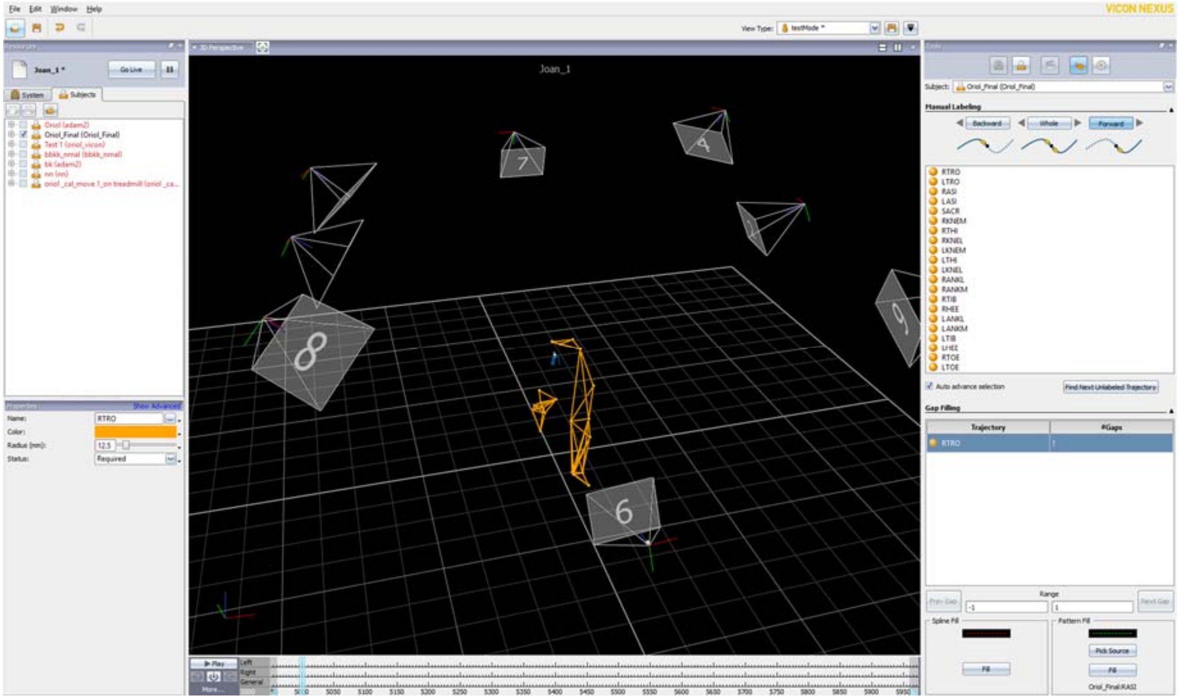
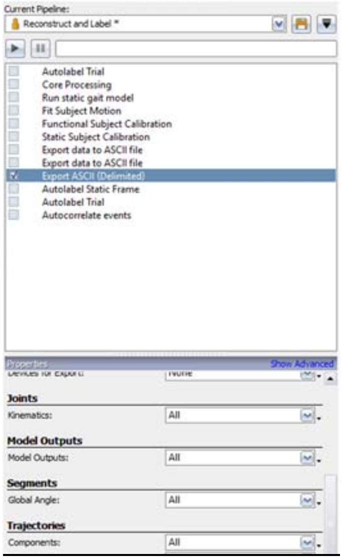


Figure 23 — Gap filling procedure. Note that there are two options in the bottom right part of the screen: “Spline fill” and “Pattern Fill”.

Once this procedure is finished, check the test again and correct the mistakes using the option “Delete Section And Unlabel Forwards” explained above. Take special attention to the last frame that you want to analyse and revise that you have the whole structure of the body.



Current Pipeline:
Reconstruct and Label *

☐ Autolabel Trial
☐ Core Processing
☐ Run static gait model
☐ Fit Subject Motion
☐ Functional Subject Calibration
☐ Static Subject Calibration
☐ Export data to ASCII file
☐ Export data to ASCII file
☑ Export ASCII (Delimited)
☐ Autolabel Static Frame
☐ Autolabel Trial
☐ Autocorrelate events

Properties
Show Advanced
Devices for Export: None

Joints
Kinematics: All

Model Outputs
Model Outputs: All

Segments
Global Angle: All

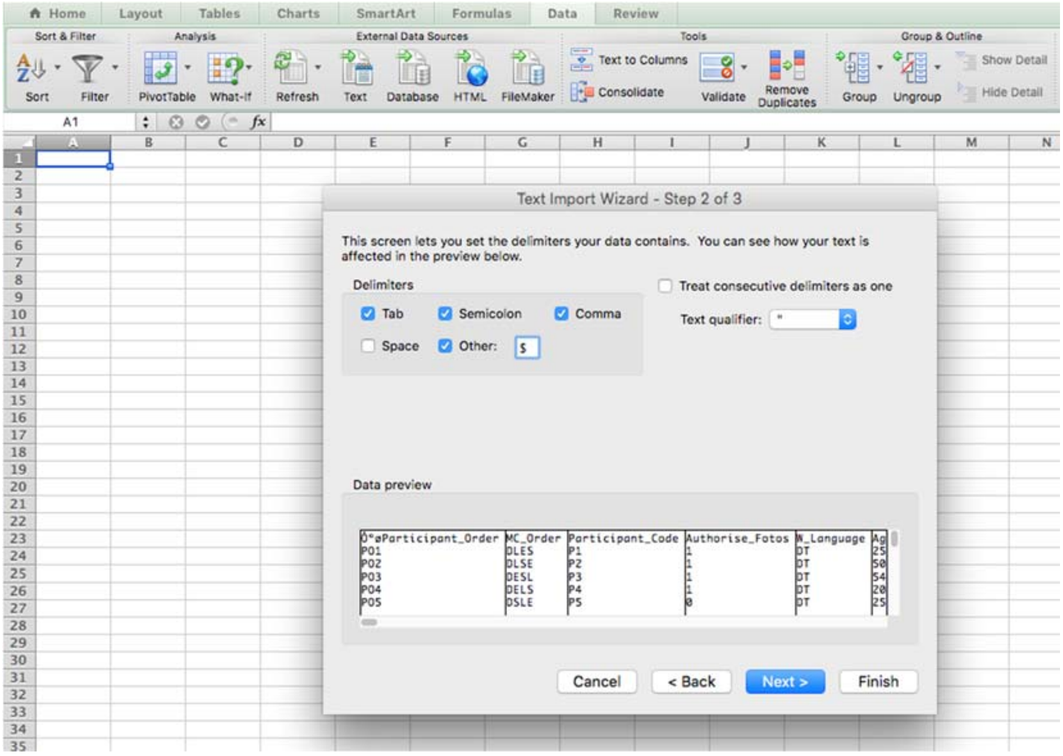
Trajectories
Components: All

Figure 24 — Export ASCII file with all the joints, outputs, segments and trajectories

Then, head to “Pipeline” check the box of “Run static gait model” and “Fit Subject Motion” and press play in the settings section.

To export the data, select the option “Export ASCII (Delimited)” and in properties select all the joints, model outputs, segments and trajectories. Press play and a “.csv” file will be created (see *Figure 26*)

In order to have all the data well organized in Excel, open a white file in Excel. In the Data tab select “obtain external data from text”, choose the .csv document, and select “Delimitated”. Click continue, select “Tab”, “Semicolon”, “Comma” and “Other: $” on the “Delimiters” (see *Figure 27*). Press “Finish” and the text will be imported in a correct structure where you can analyse all the data.



Text Import Wizard - Step 2 of 3

This screen lets you set the delimiters your data contains. You can see how your text is affected in the preview below.

Delimiters

☑ Tab ☑ Semicolon ☑ Comma

☐ Space ☑ Other: $

☐ Treat consecutive delimiters as one

Text qualifier: "

Data preview

Ö°øParticipant_Order	MC_Order	Participant_Code	Authorise_Fotos	N_Language	Ag
P01	DLES	P1	1	DT	25
P02	DLSE	P2	1	DT	50
P03	DESL	P3	1	DT	54
P04	DELS	P4	1	DT	20
P05	DSLE	P5	0	DT	25

Figure 25 — Import from the ".csv" file to more understandable Excel file.

6. Results and Interpretation

As it has been commented in the previous sections, a lot of data has been recorded and extracted from the experiments. Nonetheless, it has been decided to only analyse the stationary state of each test. From Moticon the second 50 seconds of running (from 00:50 until 1:40) have been studied and from Vicon a 1000 frames at 120 Hz in the middle of each test (from 1:00 until 1:08). As it has been commented in the previous section, only data from the left insole has been analysed.

6.1. Calculation of Variables

6.1.1. Objective Data

6.1.1.1. Moticon Variables

This section will explain the reason behind analysing each variable and how they have been calculated in order to extract results. As it has been explained in the previous *Section 5.1*, the Software Beaker 5 was not utilized as problems with the insoles were faced during the experimental part.

1. **Average of peak forces [N]:** in order to answer the third hypothesis, in every step the peak force in N has been evaluated. Then an average of all the maximum peak forces has been done. Approximately, every subject has made 60 steps. In the Graph 1 two peaks could be seen: the lowest is the heel impact and the highest is the active peak. For our study it has been filtered the force and only the second value has been analysed, the active peak (see *Figure 28*).

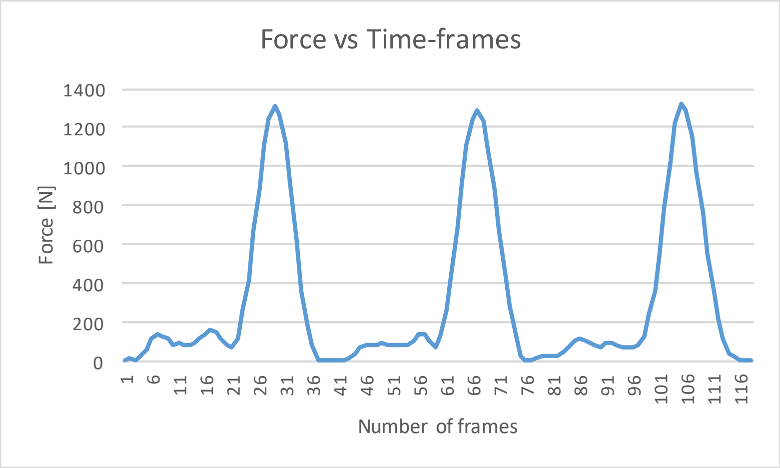


Figure 26 — Graph extracted from the raw data of Moticon.

2. **Time between peak forces [s]:** from the previous variable, the time between each peak force (s) has been extracted in order to calculate the cadence of running. After having all the values, they have been averaged.

3. **Duration of the swinging phase [s]:** to answer the fourth hypothesis, the variable has been studied from the sensor number 7 (medial region) as it has been identified as the most stable across the whole experiment. In many sensors, a lot of noise has been noticed during the swinging phase and it was impossible to create a step detector. To achieve a more refined signal a filter has been added (see *Figures 29 and 30*). Finally, the duration of the swinging phase, considered as the time with zero pressure after applying the filter, has been analysed.

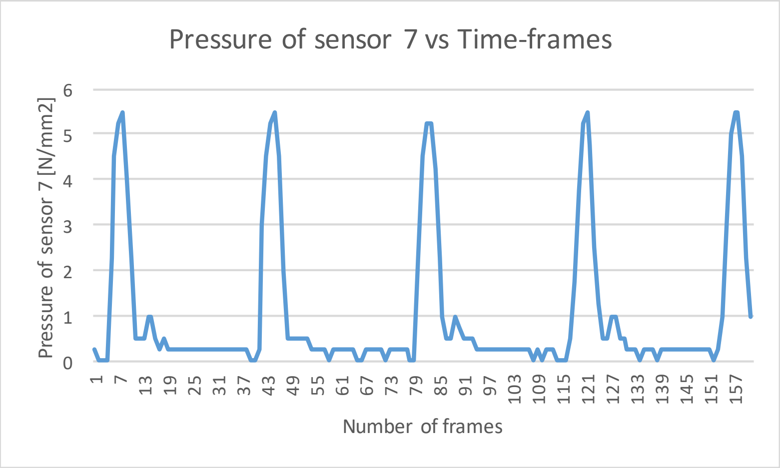


Figure 27 — Pressure evolution of the sensor number 7 without filter

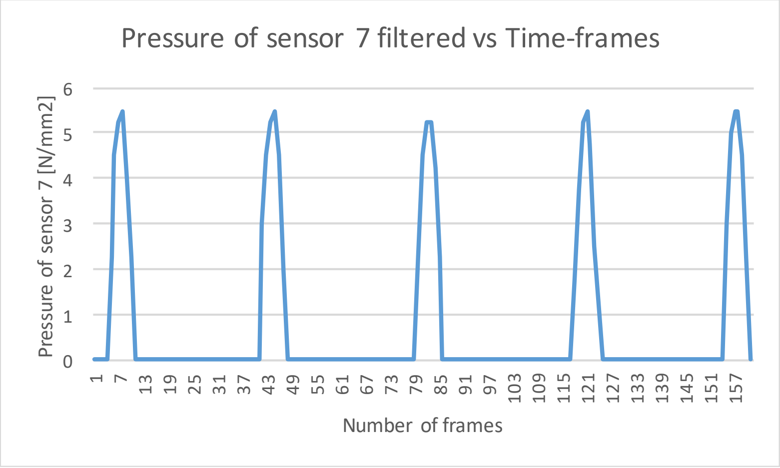


Figure 28 — Pressure evolution of the sensor number 7 applying a filter

4. **Contact time [s]:** By deducting the swinging phase to the time between the steps, the contact time has been calculated. Thus, we can drive the correct assumptions about the effect of the shoe weight in the temporal parameters.

5. **Average of the COP displacement [mm]:** it has been slightly more difficult to find this variable, as the signal coming from the raw data is very confusing (see *Figure 31*). After filtering this signal, it can be seen in the *Figure 32* the left COP in the X direction [mm].

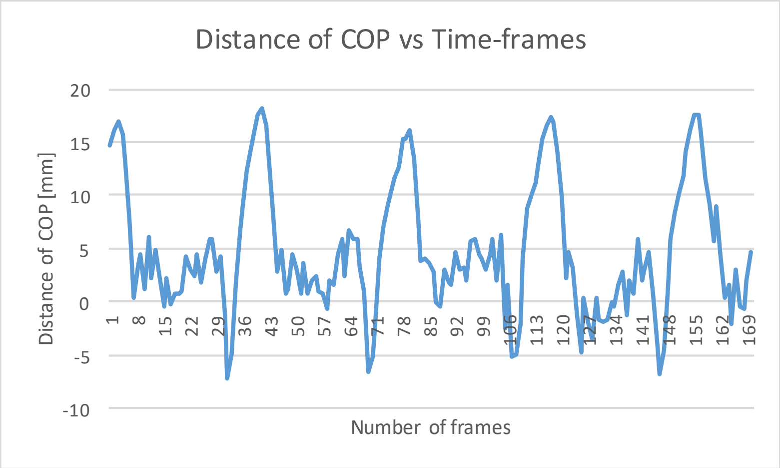


Figure 29 — Distance of the COP without filtering the signal

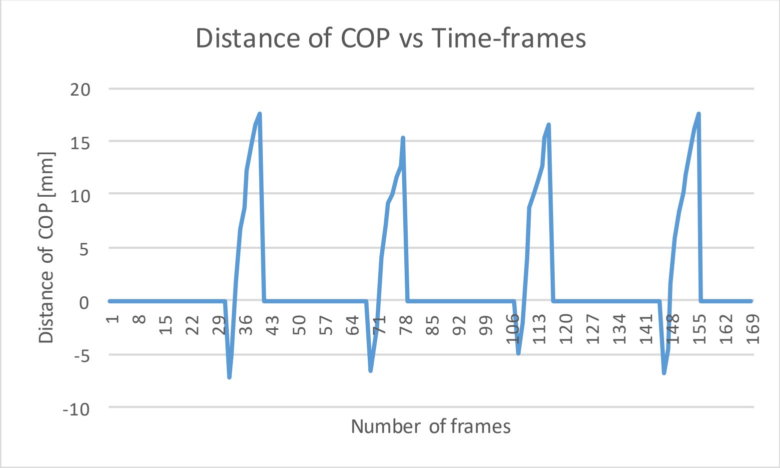


Figure 30 — Distance of the COP applying a filter

By making the same with the Y direction, the distance at time t can be calculated as follows:

$$D_{COPt} = \sqrt{\left(COPx_{(t-1)} - COPx_{(t)}\right)^2 + \left(COPy_{(t-1)} - COPy_{(t)}\right)^2}$$

Once all the distances have been computed, they have been added and divided by number of steps realized in order to get the average of each step.

6. **Average of the COP velocity [mm/s]**: the previously extracted COP displacement has been divided by the total contact time during the stance phase to get the velocity of the COP.

7. **Pressure on the forefoot [N/mm^2]:** in order to find differences between pressure distributions, the pressure of the 7 forefoot sensors from Moticon have been summed up and divided between 7. Finally, this average has been added up and divided between the total number of frames recorded in 50 seconds.

8. **Pressure on the rearfoot [N/mm^2]:** same procedure has been followed for the 6 rearfoot sensors left.

9. **Average pressure for every sensor [N/mm^2]:** to obtain more specific information, the pressure for each sensor during the 50 seconds has been averaged.

6.1.1.2. Vicon Variables

The study of this software has been slightly smaller as the tedious task of connecting the reflectors frame by frame has slowed down the total analysing job. As commented in the previous section, only the study of approximately 10 steps has been carried out (1000 frames).

10. **Maximal knee flexion angle during stance [º]:** in order to answer the fifth hypothesis, the knee angle evolution has been extracted from the raw data, as the *Figure 33* shows.

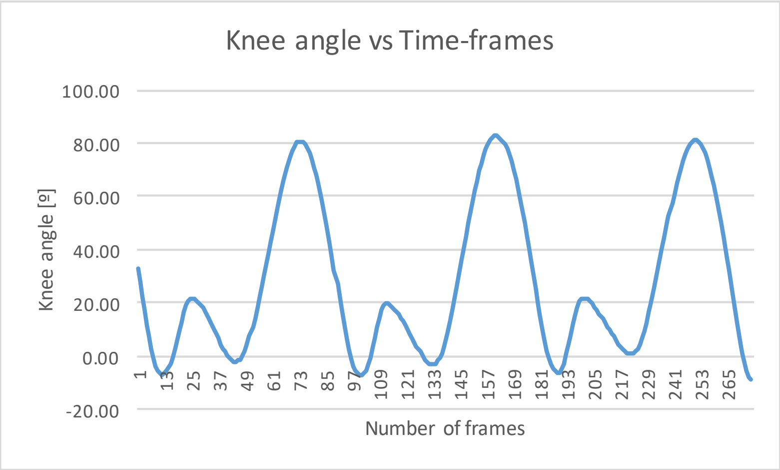


Figure 31 — Evolution of the knee angle. Representation of three steps' knee angle evolution.

From the graph above, two differentiated peaks can be detected. The lower one is the maximal knee flexion angle during the stance phase and the higher during the swinging phase. By summing all the lower peaks and dividing the result between the number of steps recorded, this variable has been calculated.

11. **Maximal knee flexion angle during swinging [º]:** as it has been done with the previous variable, the second peak of the *Figure 33* has been averaged in the stationary state.

12. **Time between maximal angles [s]**: from the previous two variables the distance between peaks has been calculated. To compare it to the time obtained with the Moticon system, these variables have been added and divided by 2 to get the average.

6.1.1.3. Garmin Variable

13. **Heart rate frequency [bpm]:** Finally, the heart rate has been measured at the end of each test. This dependent variable has given us the opportunity to check that the exertion of the subjects has no impact on the results.

6.1.2. Subjective Data

From the questionnaire, two variables have been analysed in order to answer the eighth and ninth hypothesis:

1. **Difference weight shoe [%]:** As it has been explained in the Section 4.2, after every two tests, the subjects have answered whether they have noticed a difference or not between the last two running shoes. By taking the values from the 100mm VAS question it has been easy to extract the value in a %.

2. **Confidence of answer [%]:** If the volunteer has noticed a difference in the weight, he has been asked about his level of sureness on his answer. Also, as it is a 100mm VAS question, the extrapolation of the results has been simple.

6.2. Variables Management

A total number of 13 objective and 2 subjective variables have been studied. Each variable has 16 values for every participant, as they have covered from the first test N→N until the last one C→N. To manage this amount of values the following approach has been proposed:

Values from null condition have been averaged for the increasing weight section. Same procedure has been followed for the decreasing phase. After this, the absolute value of every weight has been disposed in columns and divided in two groups: increasing and decreasing phase, as it can be seen in the *Table 4*.

Time between steps [s]	First Phase				Second Phase			
Subject	N	A	B	C	N	A	B	C
1	0.7628	0.7641	0.7703	0.7784	0.7617	0.7653	0.7768	0.7733
2	0.7308	0.7373	0.7418	0.7495	0.7362	0.7352	0.7412	0.7625
3	0.8025	0.8143	0.8016	0.8147	0.8144	0.8103	0.8121	0.8200
4	0.7752	0.7733	0.7778	0.7894	0.7803	0.7714	0.7844	0.7906
5	0.8273	0.8363	0.8459	0.8459	0.8294	0.8339	0.8452	0.8476
6	0.8901	0.9015	0.9015	0.8953	0.8792	0.8880	0.8749	0.8771
7	0.8270	0.8160	0.8561	0.8264	0.8168	0.8227	0.8336	0.8424
8	0.7691	0.7641	0.7709	0.7784	0.7616	0.7634	0.7641	0.7945
9	0.7252	0.7271	0.7330	0.7400	0.7287	0.7218	0.7359	0.7373
10	0.8157	0.8140	0.8341	0.8143	0.8095	0.8137	0.8095	0.8183
11	0.7197	0.7224	0.7307	0.7342	0.7326	0.7418	0.7436	0.7376
12	0.7845	0.7903	0.8060	0.7913	0.7669	0.7771	0.7756	0.7813
13	0.7527	0.7555	0.7525	0.7575	0.7599	0.7653	0.7711	0.7749
14	0.7768	0.7819	0.7877	0.7910	0.7723	0.7663	0.7749	0.7877
15	0.7258	0.7235	0.7327	0.7375	0.7284	0.7318	0.7368	0.7397
16	0.7213	0.7437	0.7575	0.7421	0.7409	0.7358	0.7442	0.7572

Table 4 — Values of the time between steps for every participant. The results are split first in phases and then in weights. The five control conditions for each phase has been averaged in the N column.

6.3. Results

The results of eighteen healthy (age: 25±2 years; height: 179±7 cm; body mass: 74±6 kg) participants without lower extremity injuries have been studied. All the subjects were not professional runners but they have a routine of at least 3 hours of sport per week. During the experiment none of them have reported any injuries. Nonetheless, 3 of them have reported a little discomfort in the medial part of the insole, as it is the place where the batteries are placed.

To start with the statistical study, for each weight and variable a normality test has been done, calculating the Shapiro-Wilk p-value. If this value is lower 0.05 (95% of interval of confidence) the normality hypothesis is rejected. Due to the low number of subjects and the big fluctuations of the measures, a lot of data has not fulfilled the normality requirement.

Only with the variables and weights that have been determined as normally distributed, a paired t-test with 95% has been done. When the results have not showed a normal distribution, a non-parametric Kruskal-Wallis test with 95% IC has been performed. The results of this analysis have given the possibility to detect whether the mean values are statistically different or not.

Taking into consideration that only 15 subjects for Moticon and 8 for Vicon have been analysed, the confidence level on these results is not really high. Also, the damaged pressure insoles from Moticon have not helped to drive strong correlations. In order to detect possible patterns, the mean of every variable has been represented in different graphs and proposed as possible tendencies.

6.3.1. Pressure Distribution

6.3.1.1. Pressure Sensors

For the pressure distribution, 12 sensors out of 13 have been studied. As it has been previously commented on *Section 5.1*, the sensor number 9 got damaged and it was decided not taking it into consideration (see *Figure 34*).

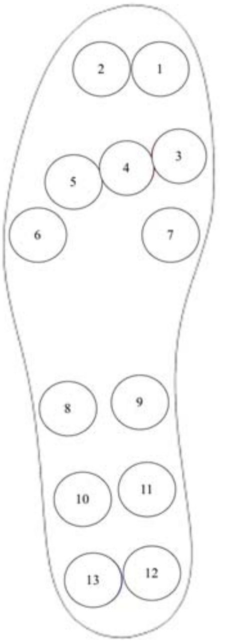


Figure 32 — Distribution of sensors for the Moticon Insole. Sensor number 9 was damaged in some tests.

On the absolute values, no statistical differences have been found. Due to the non-normality of the pressures, it has not been possible measure the difference between the results for the pressure values. The correlation index has been also calculated with the Pearson coefficient in order to measure the reliability between increasing and decreasing the weight. These values have been greater than 90% in 7 sensors, and the 50 grams' coefficient has been the lowest in 8 out of 12.

Some patterns have been found regarding the average results. In almost every sensor, 9 out of 12, higher pressures during the second phase have been detected (see *Figure 35*).

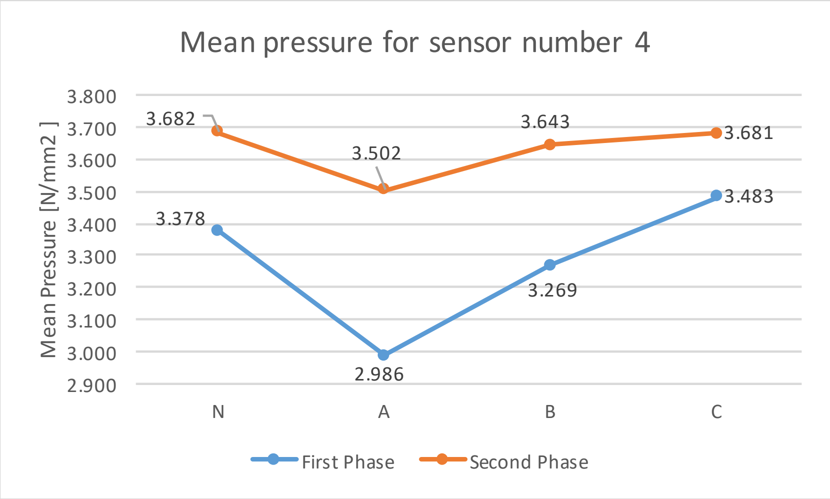


Figure 33 — Representation mean of pressure for the sensor number 4 divided in two phases with different weight conditions (N, A, B and C).

Regarding the first phase, while increasing the weight, an upward trend from 50 to 315 grams can be seen in 6 sensors. During the decreasing section, a similar pattern could be seen in 8 sensors, but with a peak pressure in the 150 grams' conditions (see *Figure 36*).

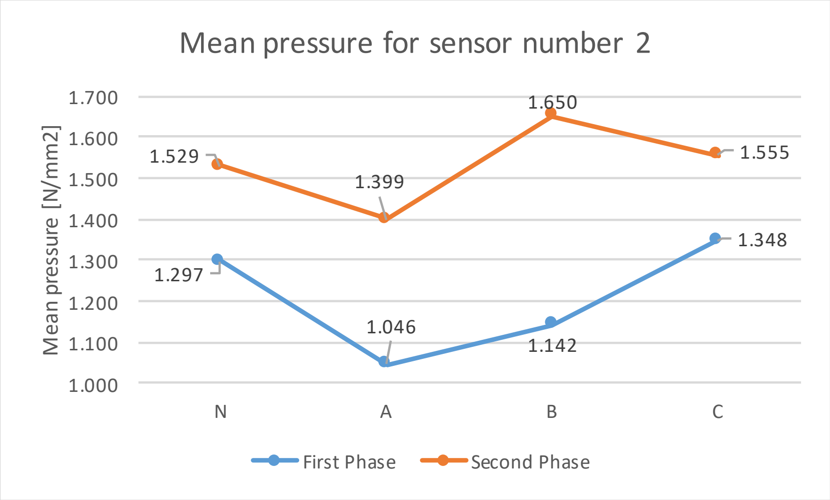


Figure 34 — Representation mean of pressure for the sensor number 2 divided in two phases with different weight conditions (N, A, B and C). Note the peak in the B condition on the second phase.

Lastly, it has been detected that the four higher values of each weight combination are always placed in the head of the metatarsal bones (sensors 3, 4, 5 and 6). In contrast, the three lowest values are placed always in the heel region (sensors 11, 12, 13) as shown in the *Figure 37*.

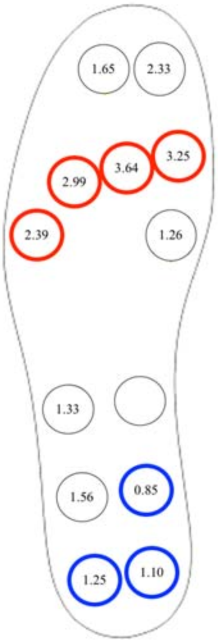


Figure 35 — Mean pressure for the B condition in the first phase. In red the highest pressure values and in blue the lowest. This pattern is the same for the whole experiment conditions.

6.3.1.2. Forefoot and Rearfoot Pressure

Taking all the seven forefoot sensors into consideration, the mean average for each test has not been normally distributed. (*Figure 38*)

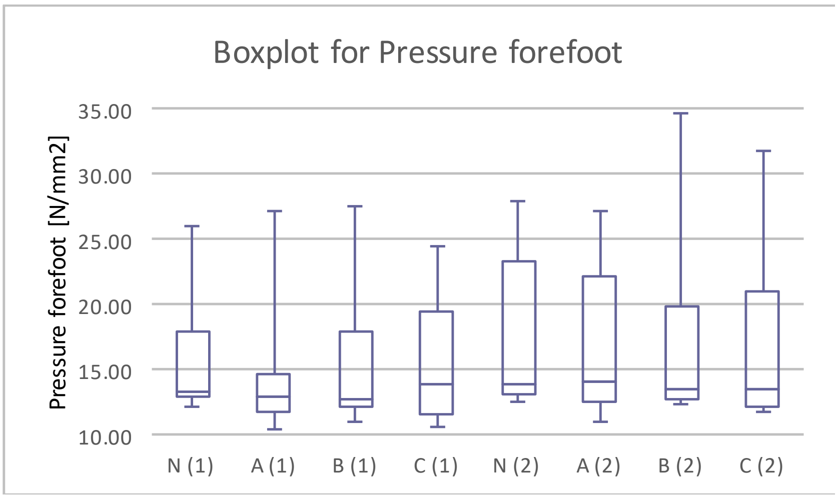


Figure 36 — Box plot for forefoot pressures. It can be noticed the non-normal distribution in none of the variables. (1) for the first phase; (2) for the second phase.

Once the non-parametric test (Kruskal-Wallis) has been run, statistical differences have been identified between Neutral (N) (16.25±4.77 MPa) and 50 grams (A)

(14.38±4.45 MPa), N and B (150 grams) (15.28±4.83 MPa), N and C (315 grams)(16.00±4.98 MPa), A and C when increasing the weight and differences only between N (17.37±5.65 MPa) and C (16.71±7.16 MPa) for the decreasing phase. When comparing the first and the second phase, all the pressures, except for C, are significantly higher in the decreasing section, as the reader can see in the *Figure 39*. Nonetheless, during the whole experiment, the pressure is always higher in the second phase.

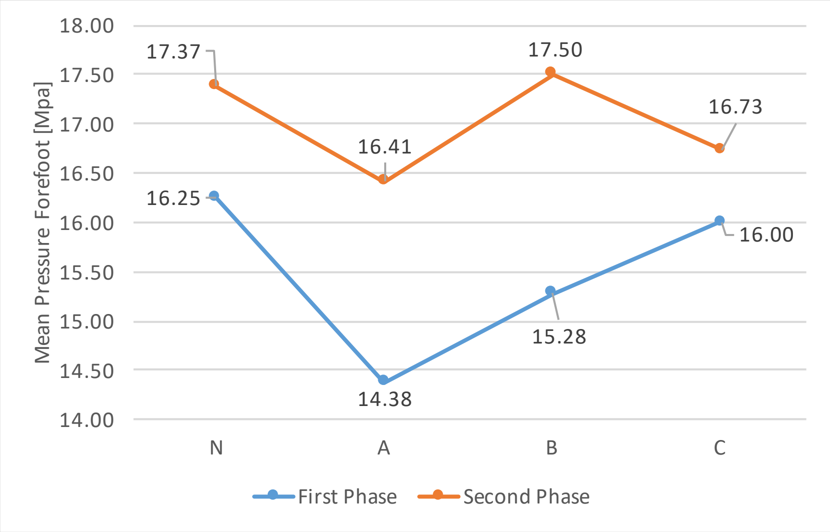


Figure 37 — Mean pressure of the 7 sensors on the forefoot. Clear increasing of pressure in the second phase.

Looking at the 5 rearfoot pressure sensors, that have worked during the whole tests, not all the data is normally distributed[1] and the Kruskal-Wallis test has shown significant differences between N (5.597±2.106 MPa) and C (5.215±2.160 MPa) when increasing the weight, between N (6.538±2.498 MPa) and A (5.714±2.161 MPa), B (6.288±3.179 MPa), C (6.099±2.866 MPa) and between A and B in the second phase. Only statistical differences have been detected when comparing the two phases for the Null condition and 150 grams. As it has been commented regarding the forefoot, in the second phase the pressure has been always higher than in the first phase (see *Figure 40*).

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[1] For more information about the normality distribution see *Boxplots*

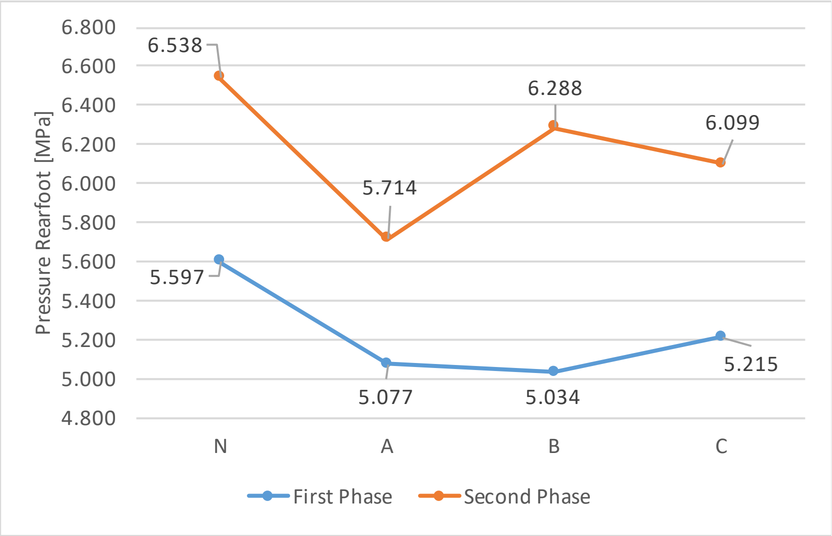

Figure 38 — Mean pressure of the 5 sensors on the rearfoot. Increasing pressure in the second phase.

6.3.2. Gait Line

For the gait line two important parameters have been studied: the covered distance of the Center Of Pressures (COP) and its velocity. A mix of normal variables and not normal distributions has been recognized for the gait line analysis[1]. As it has been introduced before, for data with normal distributions a t-test has been performed, while a Kruskal-Wallis for the non-parametric combinations has been taken ahead. In the first phase, statistical differences have been detected between N (117.0±23.6 mm) and A (129.0±28.6 mm), A and C (115.4±28.7 mm), whereas in the decreasing section only between A (121.0±25.8 mm) and C (115.2±28.7 mm). When comparing the two phases, no statistical differences have been revealed. However, the *Figure 41* shows that the gait line is always shorter when decreasing the shoe weight and converges on the heaviest shoe.

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[1] For more information about the normality distribution see *Boxplots*

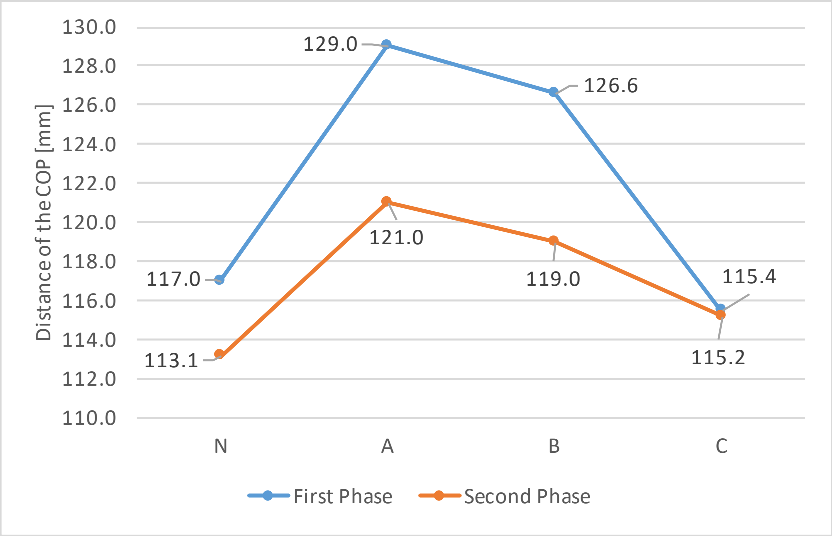

Figure 39 — Distance of the COP for the different weight combinations. Lower gait line in the second phase but converge for 315 grams.

Regarding the velocity of the gait line, all values except for 50 grams on the first phase have described a normal distribution.

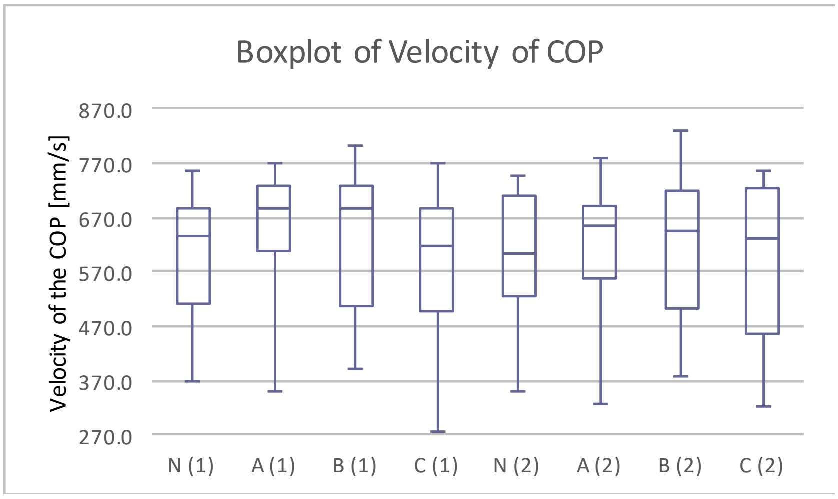

Figure 40 — Box plot of the COP velocity. All normally distributed except B (1). (1) for the first phase; (2) for the second phase.

In addition, only statistical differences between null condition (598.5±119.5 mm/s) and 50 grams (639.9±129.6 mm/s) have been noticed after the non-parametric test. As it would be expected, a similar pattern has been identified for its velocity (*Figure 43*).

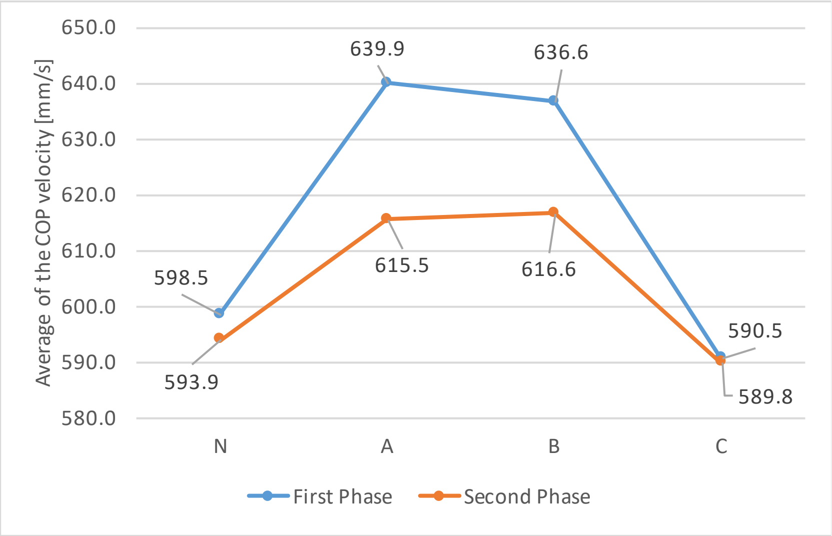

Figure 41 — Velocity of the COP [mm/s]. Lower velocities in the second phase but converge for the C condition.

6.3.3. Force

Continuing with the kinetic variables, the average of the peak forces has been studied. On the first place, the normality tests reveal that all except A and C when decreasing the weight are normal.

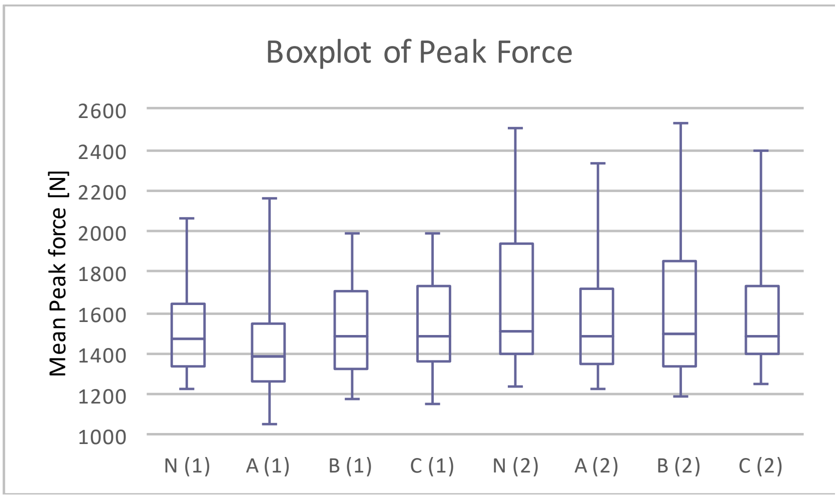

Figure 42 — Box plot of mean peak force. All the combinations are normal except A (2) and C (2). (1) for the first phase; (2) for the second phase.

Thus, the t-test have determined no statistical differences between the normal data, and the Kruskal-Wallis tests have only shown differences in the second phase between N (1656±360 N) and A (1589±344 N), N and B (1640±388 N), N and C (1602±323 N). When comparing the two phases, statistical differences have been detected for the Null condition and 50 grams. Furthermore, the correlation parameter calculated with the Pearson coefficient, revealed the high reliability between the two phases. As the reader can notice in the *Figure 45*, higher peak forces for the second phase have been identified during the whole experiment.

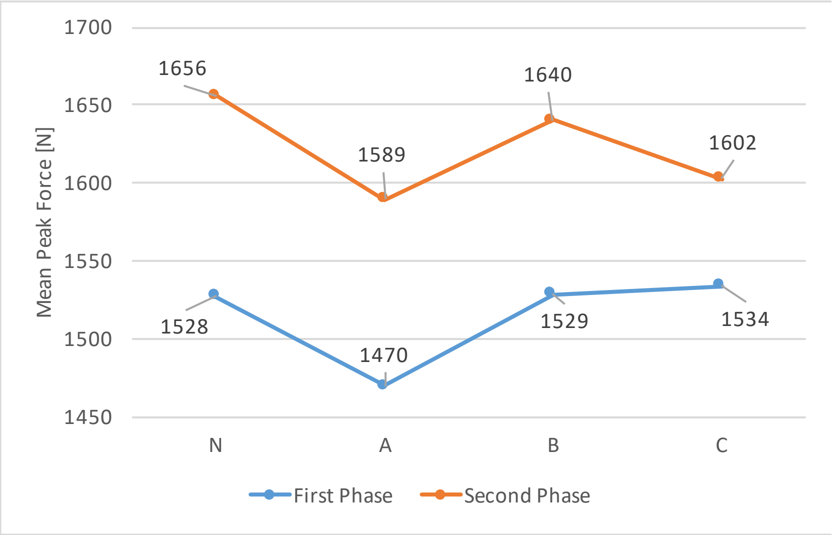

Figure 43 — Mean peak force [N]. Clear higher values of force on the second phase.

6.3.4. Kinematic Variables

Stating with the kinematic variables, after finishing the data extraction of Vicon, it has been only possible to analyse the knee angle. In further points, it will be explained how the quality of this data might be improved.

Regarding the maximal knee angle during the stance phase, all the values follow a normal distribution[1]. Nonetheless, after conducting all the t-tests, no statistical differences have been found. Concerning the correlation between the phases, high values have been determined for all the combinations. The *Figure 46* shows higher peak angles during the second phase for all the weighted and null conditions.

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[1] For more information about the normality distribution see *Boxplots*

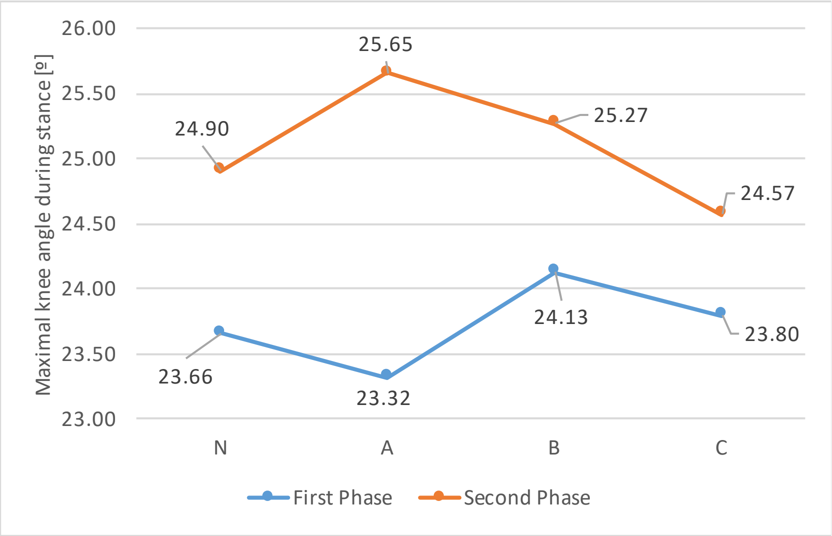

Figure 44 — Mean maximal knee angle during stance phase. Higher angles during the second phase.

While the swinging phase has been analysed, the knee angle has shown to follow a normal distribution for all the weights and phases (see *Figure 47*).

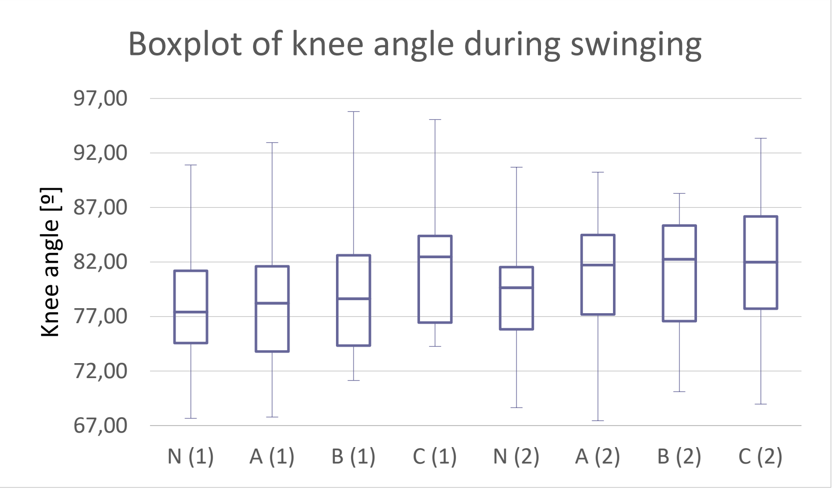

Figure 45 — Box plot of the maximal knee angle during swinging phase. All variables follow a normal distribution. (1) for the first phase; (2) for the second phase.

However, no statistical differences have been found. Their high correlation coefficients between the two phases and the clear increasing trend, showed in the *Figure 48,* illustrates to the reader the effect of the weight on this variable.

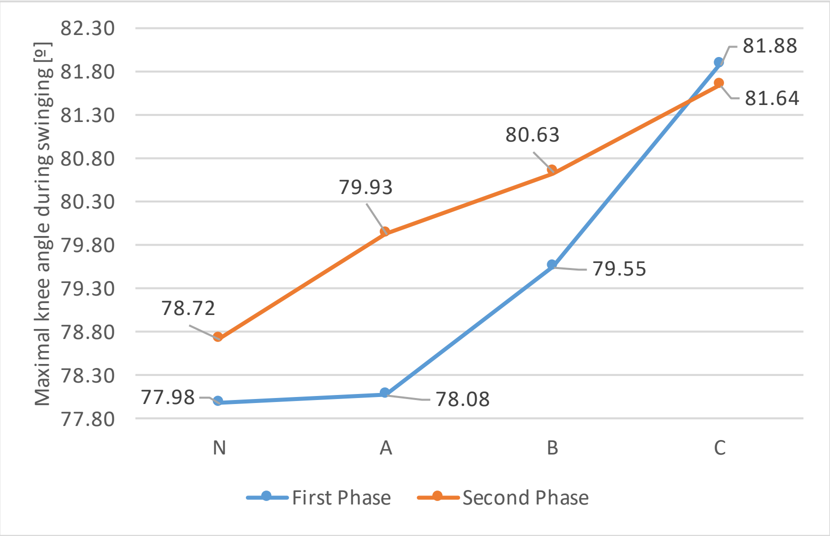

Figure 46 — Mean maximal knee angle during stance phase. Higher values in the second phase but converge for the C condition.

In order to proof this tendency, extra variables have been considered, such as the increasing angle of the knee during swinging from 0 grams to 50 grams (alpha), 150 grams (beta) and 315 (gamma). Results demonstrate that 6 out of 8 participants follow the pattern of increasing the angle gradually when increasing the shoe weights (see *Figure 47*)

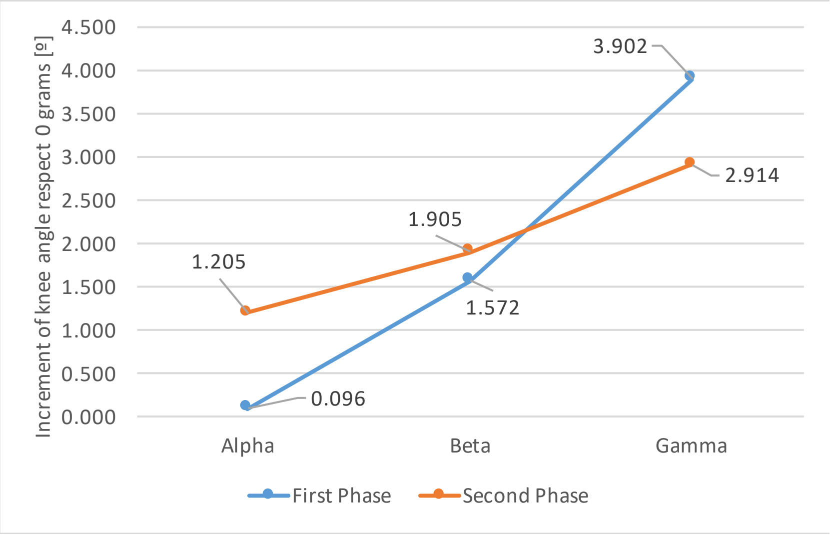

Figure 49 — Comparison of increment knee angles during swinging with respect to control condition (N).

6.3.5. Temporal Variables

Results for temporal variables have been calculated with Moticon and Vicon in order to proof their liability. Starting with Moticon, three parameters have been calculated: cycle time, swinging time and contact time.

For the cycle time, the time between peak forces has been determined. Whereas all the values follow a normal distribution, any of them show statistical differences (see *Figure 50*)

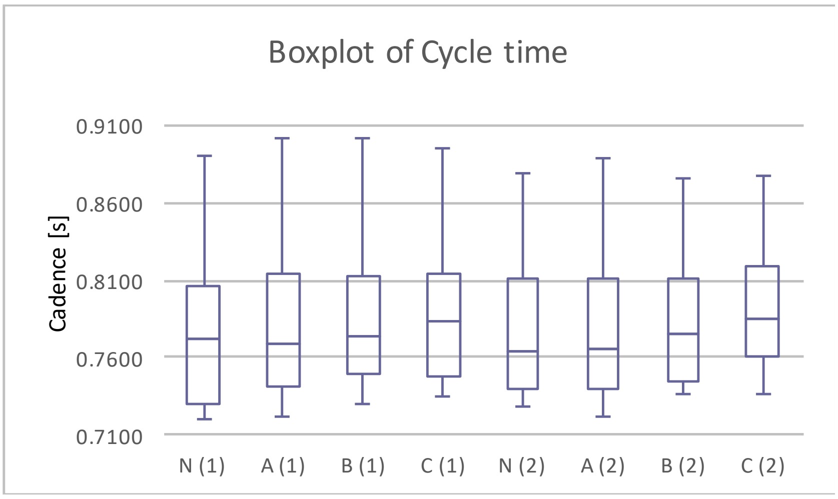

Figure 48 — Box plot of the cycle time (Distance between two peak forces). All test conditions follow a normal distribution. (1) for the first phase; (2) for the second phase.

This recurrent effect might be influenced by the low number of subjects studied. For this reason, it is very useful to detect the upward trend of the cycle time when increasing the shoe weight in the *Figure 51*.

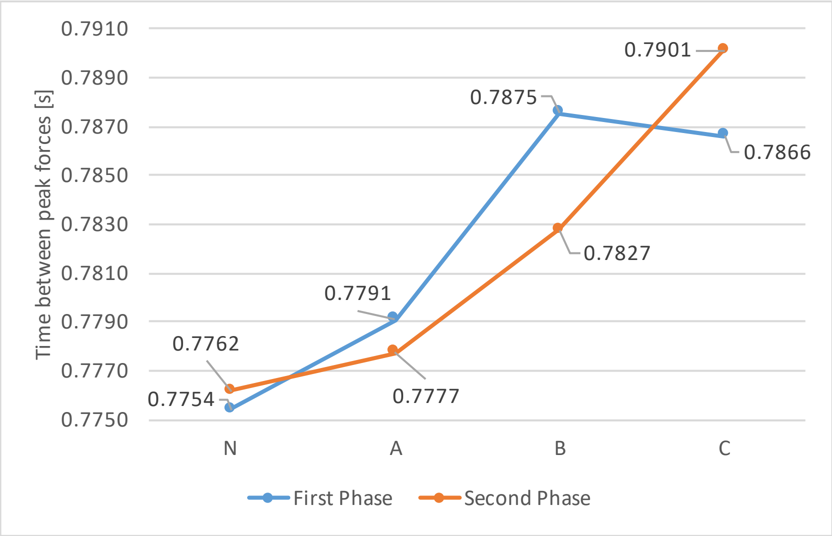

Figure 49 — Time between peak forces. Clear increasing tendency when the shoe weight increases.

After applying the filter previously exposed in the *Section 6.1.1.1*, all the swinging time values have been determined as normally distributed but with no statistical differences between the weights (see *Figure 52*).

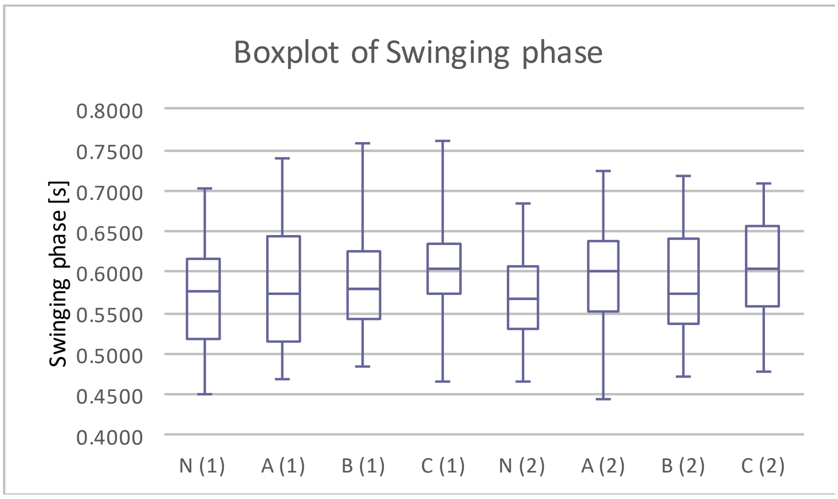

Figure 50 — Swinging phase boxplot. All possible combinations follow a normal distribution. (1) for the first phase; (2) for the second phase.

Nonetheless, the positive correlation between weight and swinging phase is evident when observing *Figure 53*.

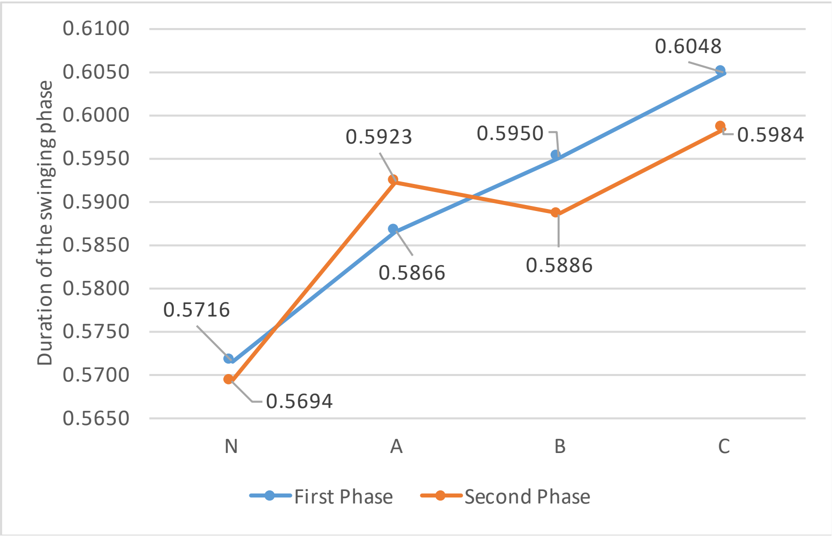

Figure 51 — Mean swinging phase times. Clear increasing tendency when the shoe is heavier.

Finally, in order to obtain the contact time, the swinging time has been subtracted from the cycle time. Repeating the previous process, all normally distributed[1] weights have shown no statistical differences. However, by looking at the *Figure 54,* a clear decreasing tendency in the first phase and a big fluctuation in the 50 grams for the second phase can be detected.

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[1] For more information about the normality distribution see *Boxplots*

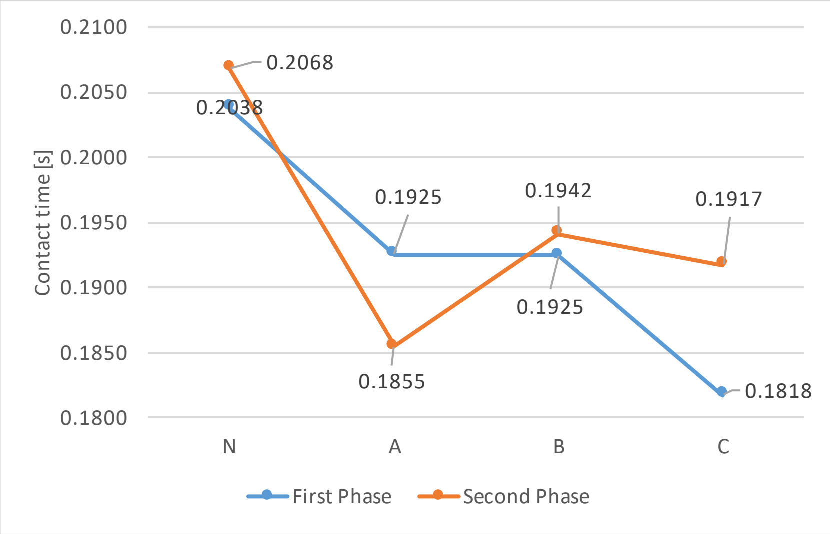

Figure 52 — Contact time. Reduction of the contact time when the shoe weight increases but lowest value for the A conditon in the secon phase.

In order to check the reliability of the data previously exposed, the distances between the maximal knee angles have been calculated and averaged. This time has been compared with the cycle of Moticon. The *Figure 55* and *56* show the most extreme results of the comparison of the 6 subjects that performed the test with Moticon and Vicon. Whereas the *Figure 55* reflects the furthest values with a total mean fluctuation of 0.76%, the *Figure 56* reveals the closest results with a total mean deviation of 0.15%. The overall fluctuation for the whole phases is of 0.36%.

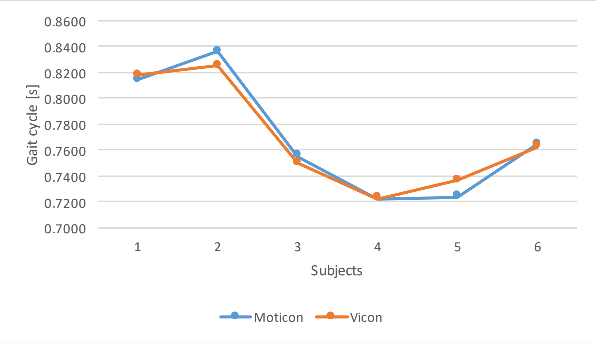

Figure 53 — Difference between Moticon and Vicon results of cycle time for the 50 grams in the first phase

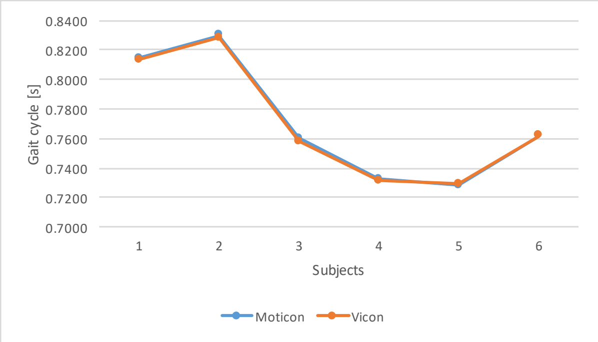

Figure 56 — Difference between Moticon and Vicon results of cycle time for the control condition in the second phase

Finally, the correlation factor has been calculated with the Pearson coefficient and all the results have values greater then 98%, reinforcing the reliability of both measurement systems (see *Table 5*).

Measure		Pearson coefficient
First phase	N	0.9994
	A	0.9874
	B	0.9989
	C	0.9969
Second phase	N	0.9997
	A	0.9981
	B	0.9974
	C	0.9975

Table 5 — Correlation coefficients of cycle time between Moticon and Vicon.

6.3.6. Heart Rate

To measure the exertion effect on the subject's performance, the analysis of the Heart Rate values has been conducted. After the verification of the normalized data, Anova tests haven't shown any significant difference between the weights and the phases.

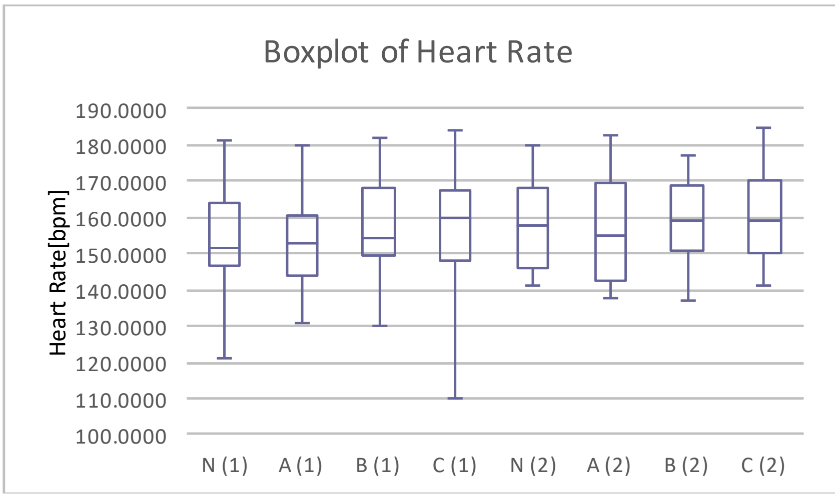

Figure 54 — Boxplot of heart rate. All the values follow a normal distribution. (1) for the first phase; (2) for the second phase.

As the reader could notice in the *Figure 57,* during the second phase the heart frequency values are always higher but not significantly. The difference between the two extreme values of the test is of a 4.96%.

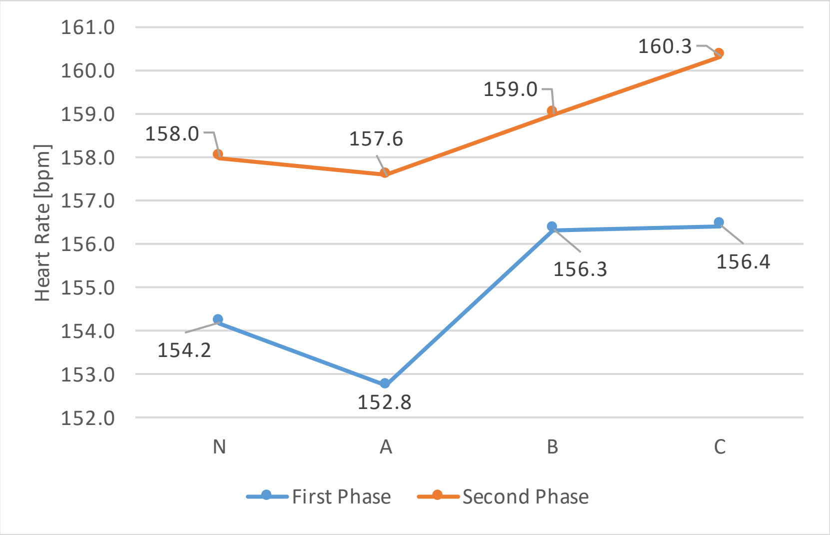

Figure 55 — Heart rate averages for each weight combination and phase. Higher values in the second phase.

6.3.7. Subjective Variables

Finally, for the subjective results, the perceived differences on the shoe weight and the confidence of the subject's answer have been studied. As expected, none of the variables have followed a normal distribution.

Regarding the perceived shoe weight, all combinations have presented statistical differences except between 50 grams and 150 grams for both phases. When comparing the increasing and decreasing stages, no different means have been detected. By looking at the *Figure 58*, a clear increasing tendency is drawn as estimated and the subjects noted more weight on the second phase.

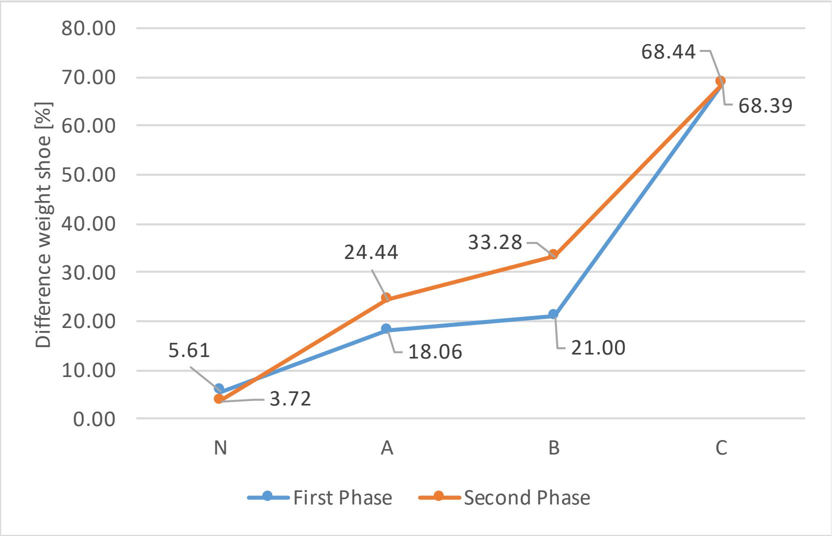

Figure 56 — Perceived weight from the subjects. Answer of the question: "*How big is the difference that you notice on the shoe weight?*"

In parallel, subjects also got more confident about their answers in the second phase, as the *Figure 59* shows. Considering the Kruskal-Wallis tests, no statistical differences between the two phases have been detected. In contrast, all the combinations within the phases have presented statistical differences except between N and A, A and B when increasing the weight and between A and B in the second phase.

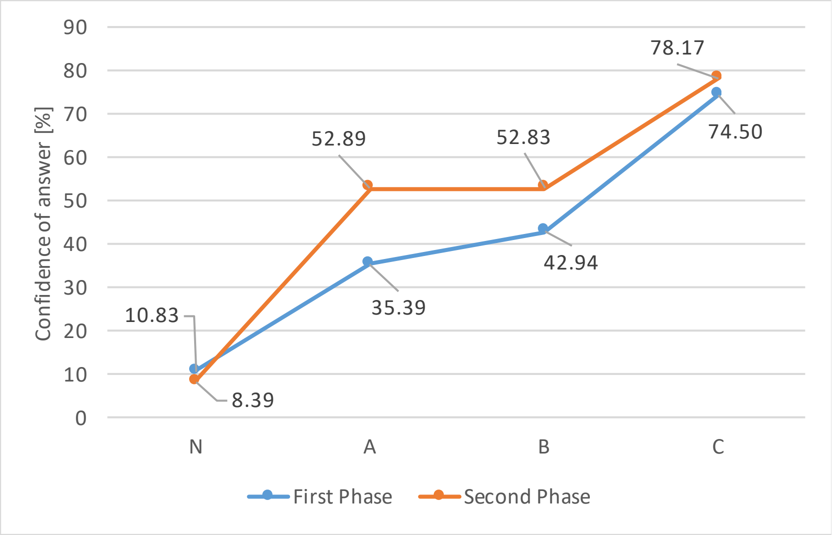

Figure 57 — Confidence of the subjects. Answer to the question: *"How much sure are about your previous answer?"*

6.4. Discussion

After carefully analysing the collected data, this section aims to expose the most interesting inferences and the relationship between the whole variables and tests. To start with the heart rate frequency, it has to be emphasised that results have revealed no exertion influence during the whole experiment. This affirmation is really important as all the interpretations below are based on non-fatigue effects.

In addition to this information, both measurement systems have been determined as reliable. No clear differences between recording the cycle time with Moticon and Vicon have been found. Thus, these results have showed the same consistency as in previous studies (Braun et al., 2015; Stöggl & Martiner, 2017).

Regarding the pressure distribution, no clear pattern has been identified, but sensors have shown that most of the participants had peak pressures in the head of the metatarsals and the lowest values were placed in the heel region. Due to the fact that all the participants were rear foot strikers, the heel should have received greater pressures, but in our study results showed the opposite pattern. The damaged sensors detected halfway through of the experimental phase might influence these results. For this reason, the second hypothesis (*3.2*), that states that the weight of the shoe has an influence on the pressure distribution, has been rejected.

When comparing the increasing and decreasing phase, pressures and peak forces have been higher in the second phase of the tests for the whole shoe weights. Also a high correlation values within the two phases has revealed the reliability of the data. Perceptions might have an effect on this results as the subjects got more confident in the second phase and this could lead to higher pressures and forces. Nonetheless, there is no evidence that the shoe weight has an effect on the peak forces as the third hypothesis (*3.3*) suggested.

By analysing the gait line, a reduction of the distance covered by the COP has been detected on the second phase of the experiment. Same pattern has been seen for the velocity of the centre of pressure. These results were expected as a reduction of the gait line causes the increasing of the pressure in the foot’s sole. Nonetheless, this relation is not linear and future research should use a more accurate pressure insole system with more sensors in order to determine this correlation.

A clearer tendency has been noticed when looking at temporal parameters. From previous sections, it can be deducted that increasing the shoe mass leads to an increase of the running cycle time. For this reason, the sixth hypothesis (*3.6*) can be accepted but increasing the number of subjects is recommendable to reinforce these results.

In addition, the individuals in our experiment have spent more time in the swinging phase with heavier shoes. This is because their balance is modified when the shoe weight increases and the natural reaction of the body is to make the steps more stable. Against the least fatigue-efficient solution, participants have increased the cycle time and swinging time but decreased the contact time inducing us to accept the fourth hypothesis (*3.4*) (*See Figure 49,Figure* **51** *andFigure* **52***).*

To reinforce these inferences, Vicon results have shown clear evidences of increasing the knee angle during the swinging phase when heavier shoes were worn. Again, the low number of subjects is not helpful in order to confirm strong affirmations. Nonetheless, a lot of the subjects that could not perform the trials with Vicon modified their running pattern by reducing their number of steps. One of the most common ways of doing this is by increasing the maximal knee angle. Due to this low possibility of recording more data we are not able to confirm neither reject the fifth hypothesis supporting the increasing of the knee angle (*3.5*).

By looking at the perceived weight, many volunteers have mixed 50 grams and 150 grams and no statistical differences have been noticed between them. Subjects clearly detect the null condition and the heaviest shoe (315 grams). These results confirmed previous studies from Slade et al. (Slade et al., 2014) affirming that lower extremities are more accurate when detecting weights greater than 140 grams.

Regarding differences from the first and second phase, no condition shows a significant change. In addition, it can be detected visually in the *Figure 56,* that for 315 grams the both means converge. This behaviour is the same for the maximal knee angle during swinging (*Figure 51*), COP velocity (*Figure 41*) and distance (*Figure 39*). As

Table **6** exhibits, the minimal difference between the first and the second phase for the four variables happens with the heaviest shoes.

Variable	N	A	B	C
Perceived difference shoe weight	-50.75%	26.14%	36.89%	-0.08%
Knee during swinging	0.94%	2.31%	1.33%	-0.30%
Distance COP	-3.41%	-6.61%	-6.37%	-0.21%
Velocity COP	-0.79%	-3.96%	-3.25%	-0.13%

Table 6 — Difference in percentage between the first phase and second phase of four variables: (1) Perceived difference of the shoe weight; (2) Mean peak knee angle during the swinging phase; (3) Distance of the COP; (4) Velocity of the COP. Note that the lowest variability is with C condition (315 grams).

It has been considered necessary to include *Figure 58* to easily confirm the same behaviour of the knee angle and the objective measurements. Note that the COP has a negative and more pronounced correlation with the objective measurements.

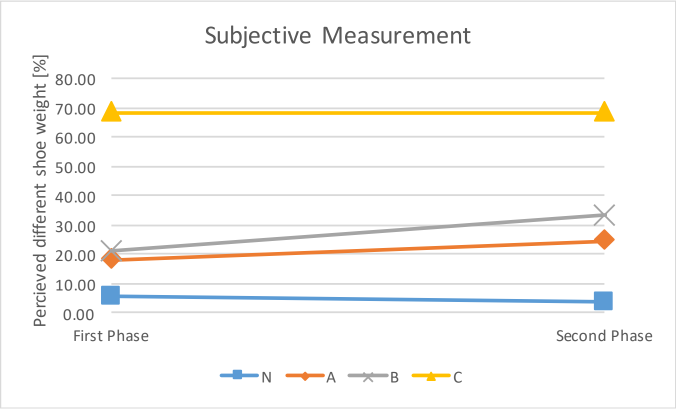

Figure 58 — Comparison between the two phases of the perceived shoe weight.

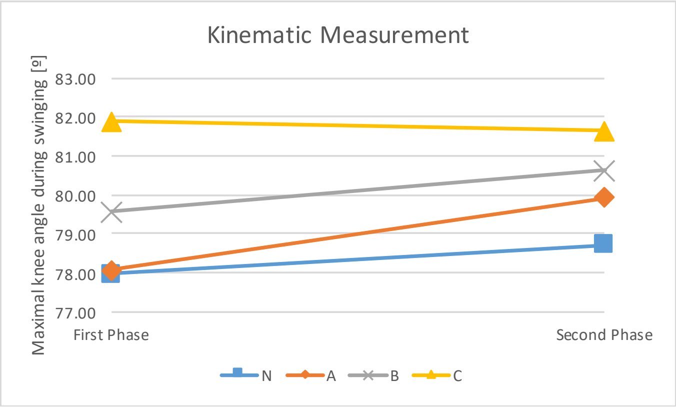

Figure 61 — Comparison between the two phases of the maximal knee angle during swinging. Almost same pattern as the subjective measurement but greater increasing in the null condition.

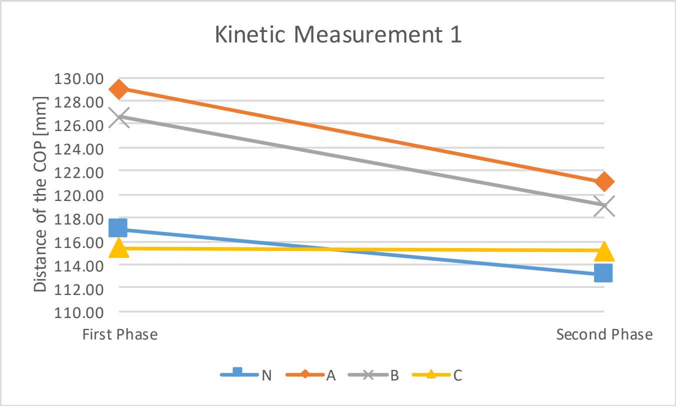

Figure 62 — Comparison between the two phases of the COP Distance. Reverse and more pronounced trend than the subjective measurement except for C condition (315 grams).

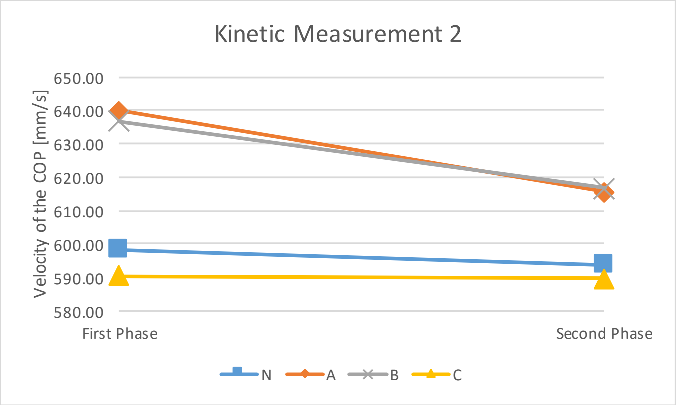

Figure 63 — Comparison between the two phases of the COP Velocity. Reverse and more pronounced trend than the subjective measurement except for N and C condition.

This leads us to infer that perceptions have an effect in some kinetic (distance and velocity of the COP) and kinematic (knee angle) parameters when an extreme weight is added to the shoe.

7. Conclusions and Further Research

Despite the multiple problems faced with Moticon and the difficulty while analysing the Vicon data, this project has shown promising results regarding the shoe weight influence on running and its relationship with perceptions.

Firstly, our study has found no changes in the pressure distribution. In addition, the constant high measures in the head of the metatarsals leads us to discuss the affirmation of Chen et al. (Chen, Nigg, Hulliger, & de Koning, 1995). In the *Section 2.2.2* it is commented that the presence of unusual peak pressures in the medial forefoot and hallux was a symptom of discomfort. Nonetheless, none of the subjects have revealed a constant discomfort or pain during the whole experiment. For this reason, we cannot determine this type of pressure distribution as a sing of discomfort.

Secondly, changes in the running pattern have been revealed when analysing temporal and kinetic parameters. A clear mass effect has been detected with the increase of the cycle time, swinging phase and the reduction of the contact time. Also, by looking at the Vicon results it can be inferred that the knee angle during swinging tends to be larger when the shoe weight increases. As it has been mentioned in the previous *Section 6.3.4*, the subjects have adapted their running cycle and this leads us to accept the first hypothesis *3.1.*

However, some considerations have to be taken into account for further research. The adaptation of the running pattern and the increment of the knee angle during swinging could be caused by the constant running speed of the treadmill. The subjects might have adapted their running cycle in order to gain stability. In the previous *Section 2.5* the possible non correlation between ground and treadmill running has been alerted (Dingwell et al., 2001; Elliott & Blanksby, 1976; Mok et al., 2009; Nelson et al., 1972; Benno M. Nigg et al., 1995; Sinclair et al., 2013). For this reason, it is suggested to perform the same trials in the ground running. Thus, the motivation for changing their running parameters can be found in that condition.

Thirdly, subjective results have showed that there is no significant difference when the shoe order is changed. By looking at the results (*Figure 57*), it can be said that people get slightly more confident in the second phase. This might have a relationship with some subjective results, such as force and pressure showing higher values in the decreasing phase. Nonetheless, assumptions made in the *Section 3.7* cannot be verified and the seventh hypothesis should be rejected.

Finally, this study confirms that people detect heavier weights than 150 grams easily and the eighth hypothesis (*3.8*) has been accepted. More in detail, results converge in the 315 grams for the first and second phase. Objective and some subjective parameters have shown this pattern and we can accept that perceptions have an effect in kinematic and kinetic parameters (*3.9*).

To conclude, this study has revealed promising results in the matter of shoe weight and its relationship with perceptions. Nonetheless, recording systems should be reconsidered and the number of subjects increased to gain more significant results in the future.

8. Acknowledgements

The finalisation of this project means a lot for my academic evolution. It is the end of one big era of my life. After many years I will become an Industrial Engineer. This is why I want to thank everybody that has helped me achieving this goal.

To begin with, I want to recognize the participation of all my friends in the experiments. Specially, I would like to remark the big support received by Victor Giménez, not only during the project, but all these years.

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I also want to thank the TUM University and the “Lerhstühl für Sports- und Materialengeräten”. Without their help and resources, the realization of this thesis would have not been possible. Obviously, the positive attitude and the great cooperation of Bahador Keshvari have helped me to enjoy and learn with this project at the same time, thank you.

With more affection, I would like to thank the enormous support and encourage received from my family during this big journey. Last but not least, thank you very much, Maria, for your huge help on this project and for being by my side at all time.

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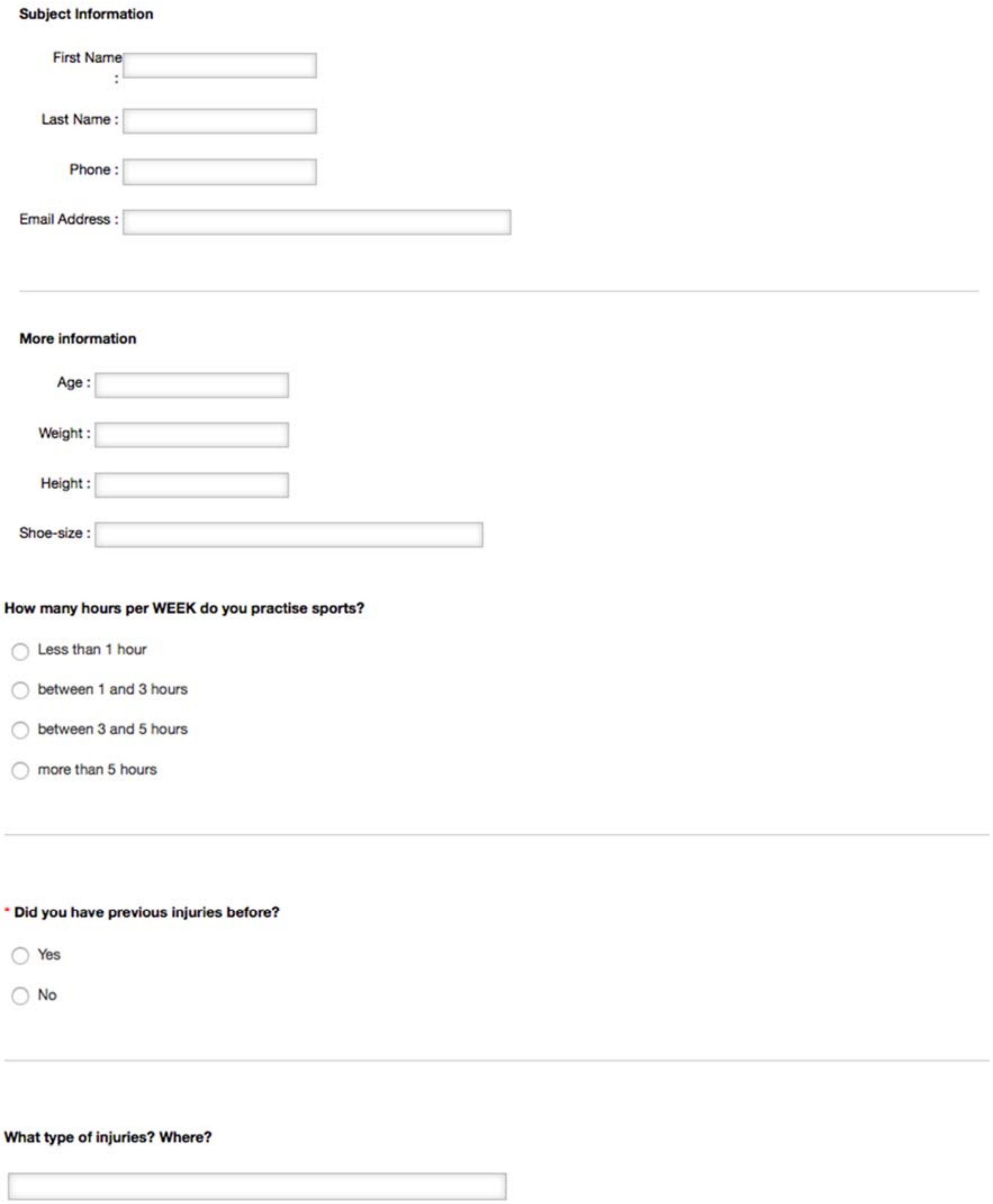
Figures

Tables

Appendix

Questionnaire



Subject Information

First Name :

Last Name :

Phone :

Email Address :

More information

Age :

Weight :

Height :

Shoe-size :

How many hours per WEEK do you practise sports?

○ Less than 1 hour

○ between 1 and 3 hours

○ between 3 and 5 hours

○ more than 5 hours

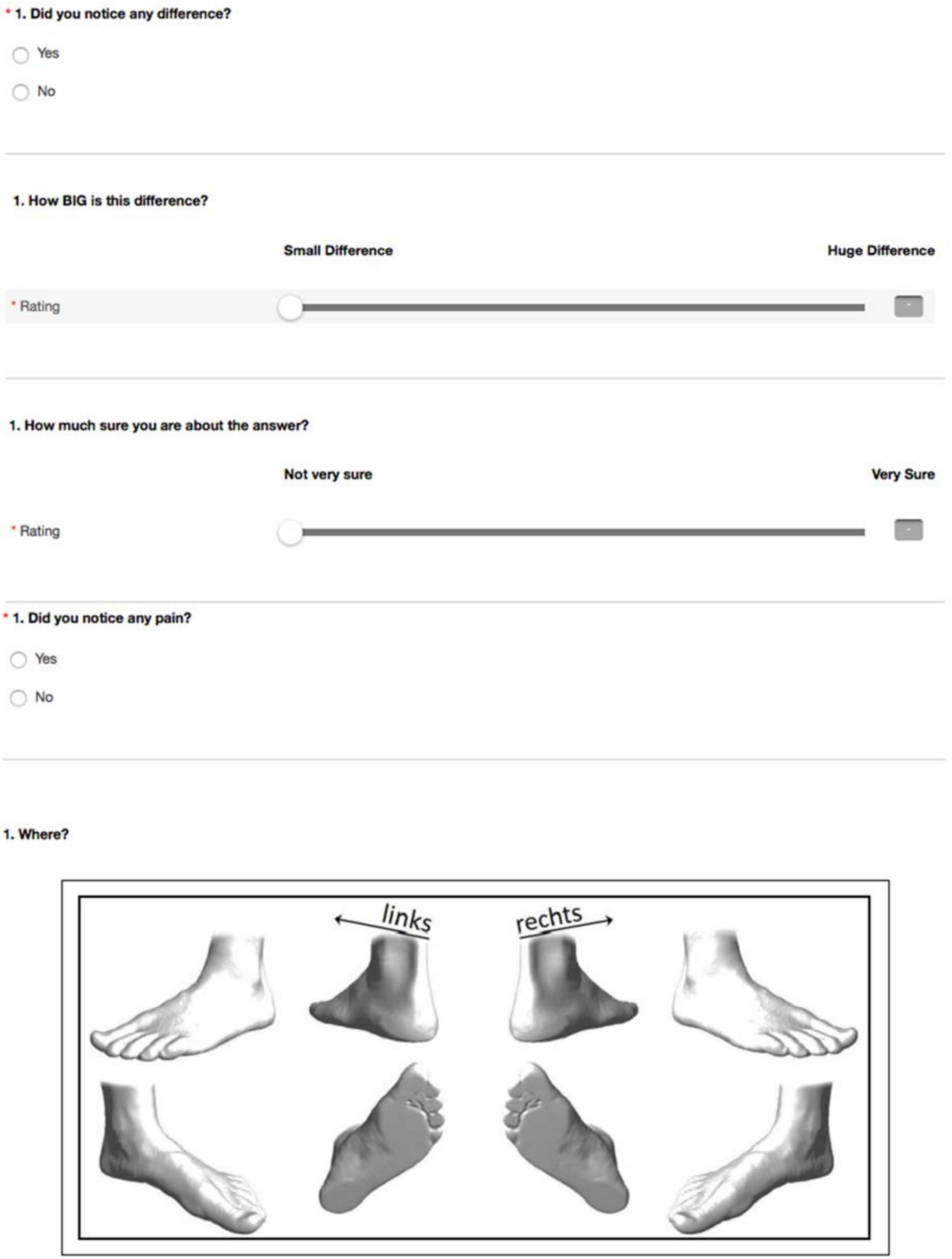
*** Did you have previous injuries before?**

○ Yes

○ No

What type of injuries? Where?

Figure 0.1— First part of the questionnaire. Questions asked before starting the tests.



* 1. Did you notice any difference?

○ Yes

○ No

1. How BIG is this difference?

Small Difference — Huge Difference

* Rating

1. How much sure you are about the answer?

Not very sure — Very Sure

* Rating

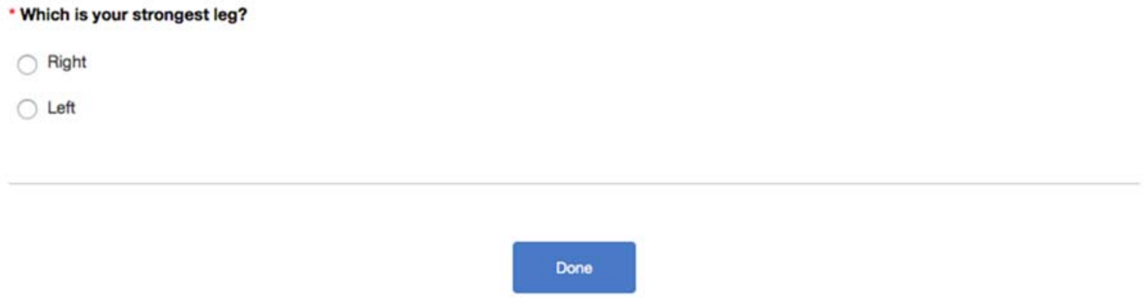
* 1. Did you notice any pain?

○ Yes

○ No

1. Where?

Figure 0.2 — Second part of the questionnaire. Questions asked once every two trials



* **Which is your strongest leg?**

○ Right

○ Left

Figure 0.3 — Third part of the questionnaire. Questions asked at the end of the experiment

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Professur für Sportgeräte und Sportmaterialien
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Garching, den 18. Januar 2018

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Figure 0.4 — Advertisement asking for volunteers

Boxplots

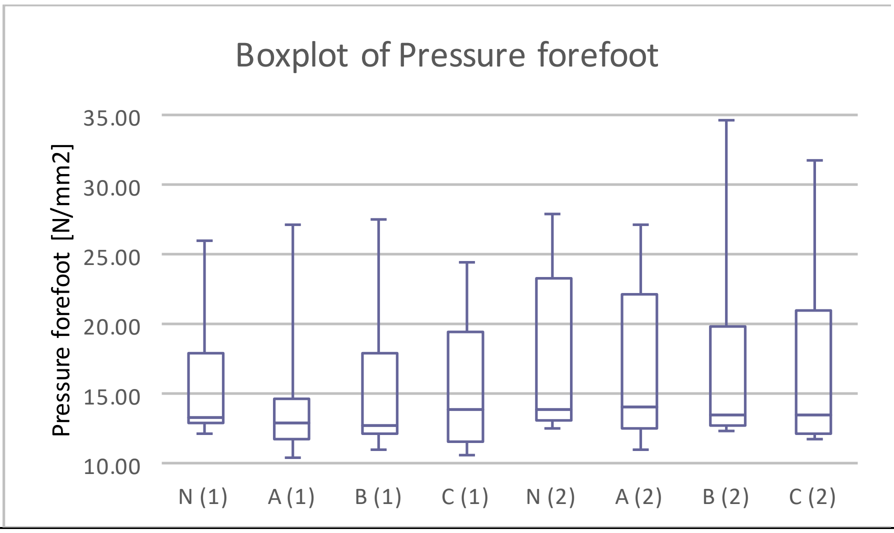

Figure 0.5 — Boxplot of pressure forefoot. (1) for the first phase; (2) for the second phase.

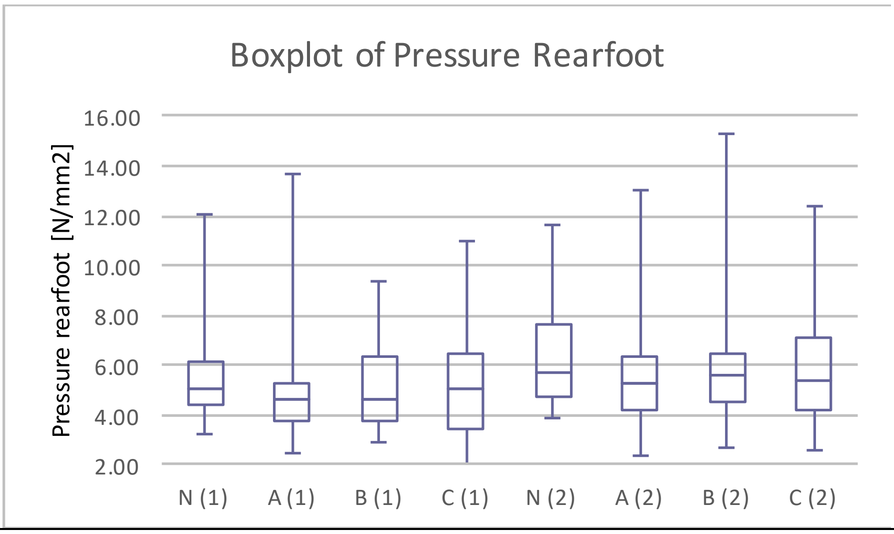

Figure 0.6 — Boxplot of pressure rearfoot. (1) for the first phase; (2) for the second phase.

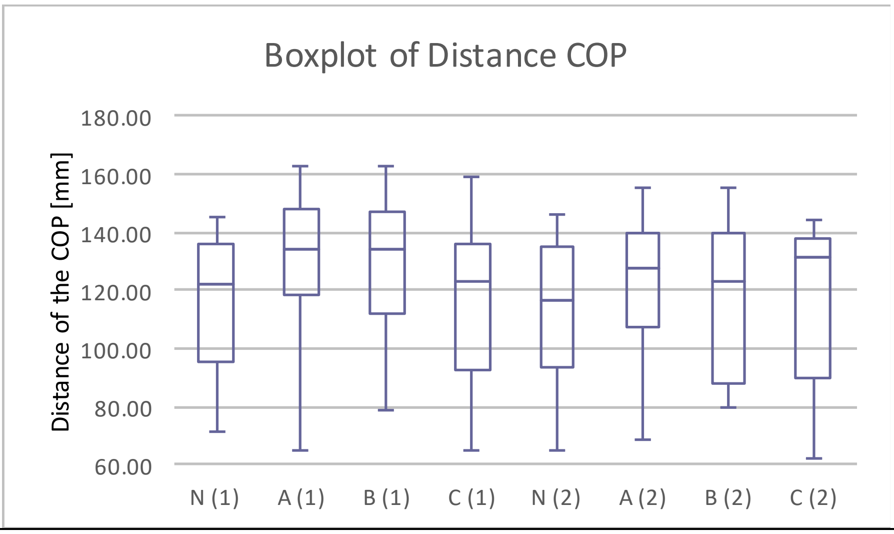

Figure 0.7 — Boxplot of Distance COP. (1) for the first phase; (2) for the second phase.

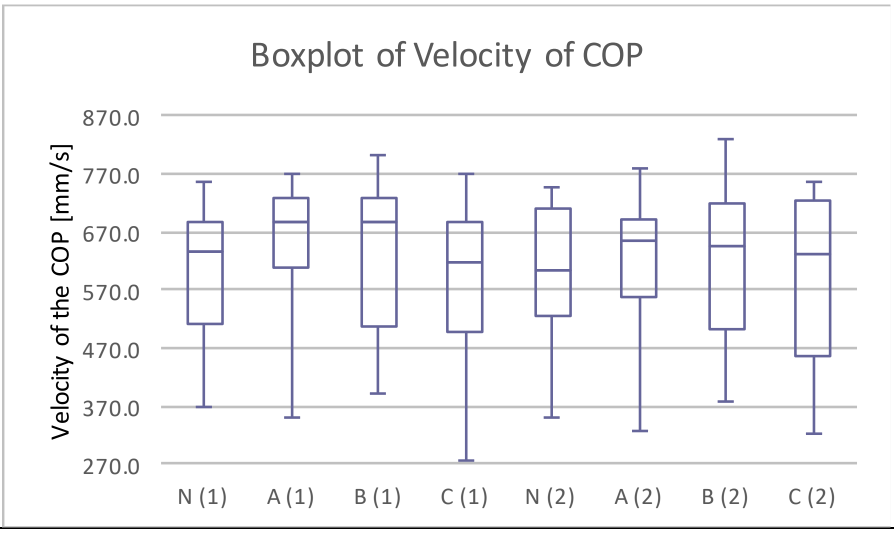

Figure 0.7 — Boxplot of COP velocity. (1) for the first phase; (2) for the second phase.

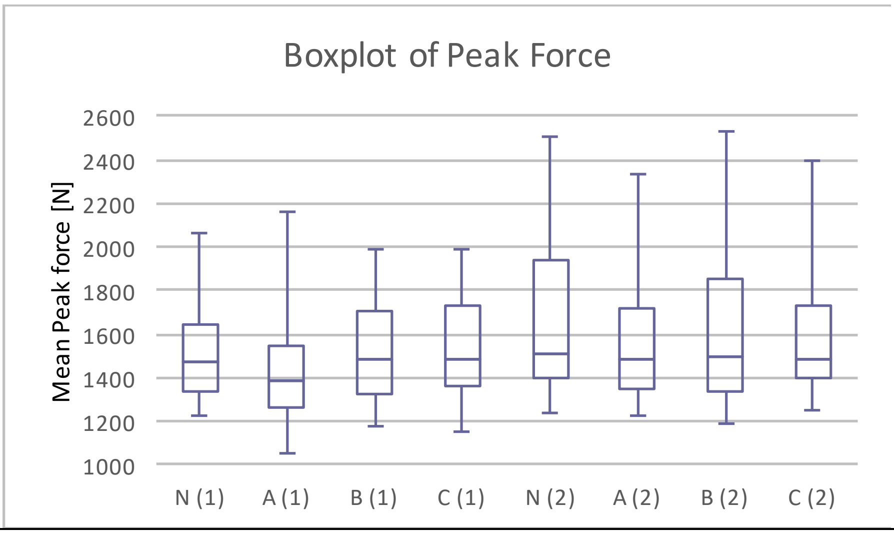

Figure 0.8 — Boxplot of mean peak force. (1) for the first phase; (2) for the second phase.

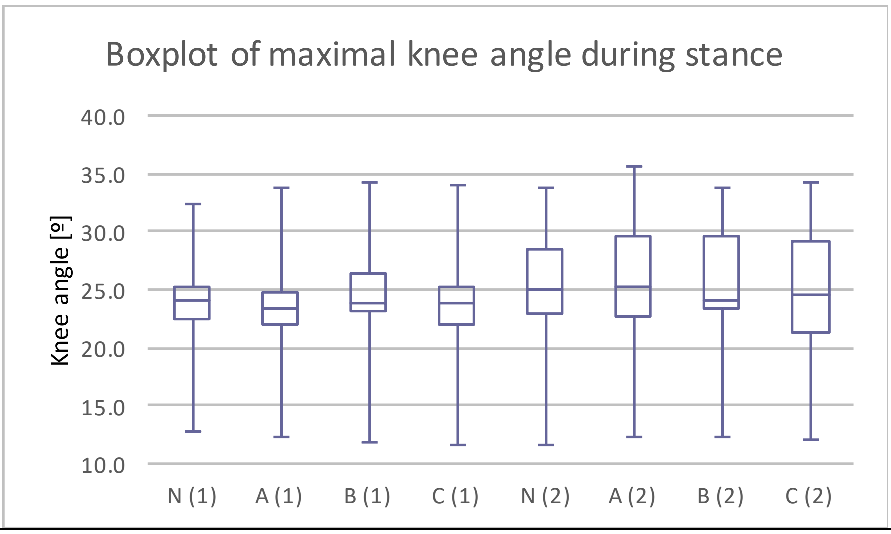

Figure 0.9 — Boxplot of maximal knee angle during stance phase. (1) for the first phase; (2) for the second phase.

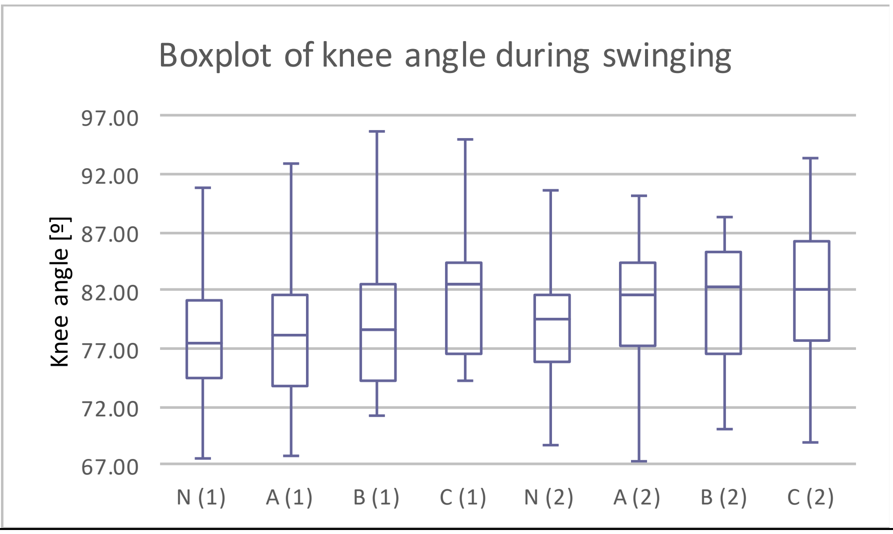

Figure 0.10 — Boxplot of maximal knee angle during swinging phase. (1) for the first phase; (2) for the second phase.

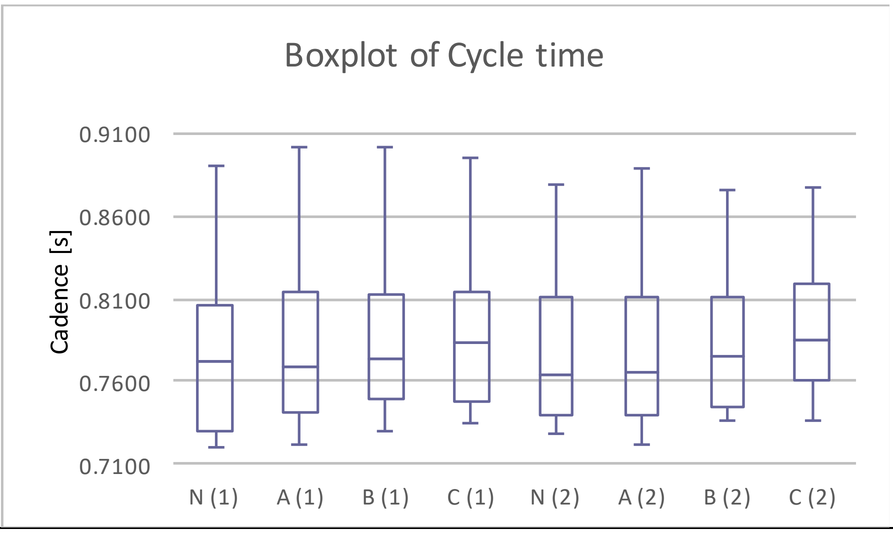

Figure 0.11 — Boxplot of cycle time. (1) for the first phase; (2) for the second phase.

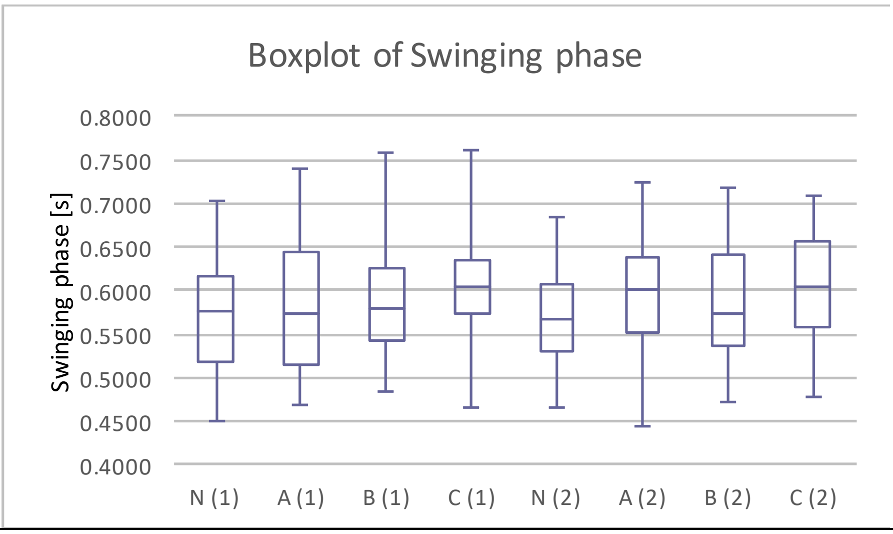

Figure 0.12 — Boxplot of swinging phase. (1) for the first phase; (2) for the second phase.

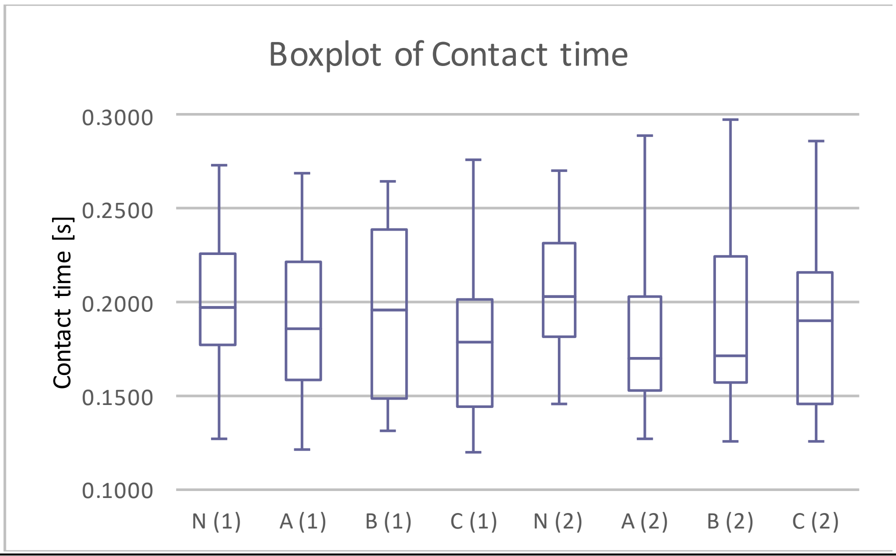

Figure 0.13 — Boxplot of contact time. (1) for the first phase; (2) for the second phase.

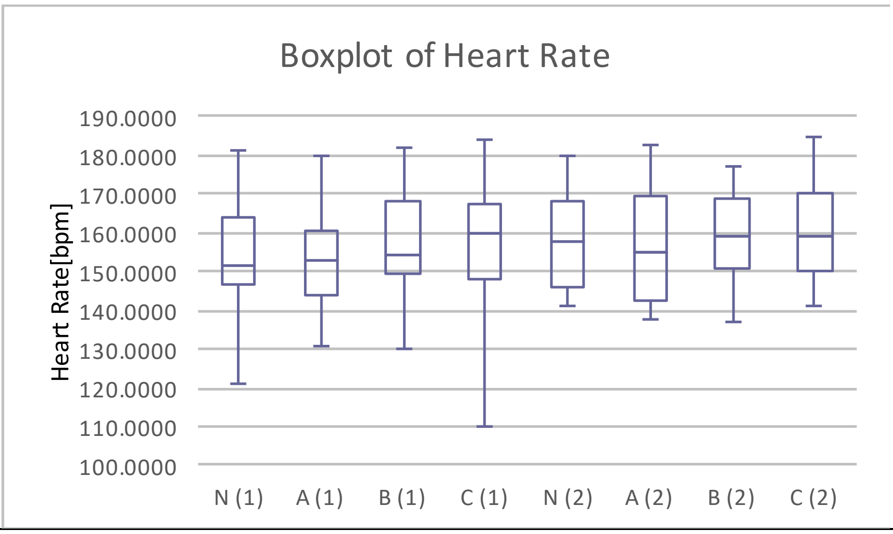

Figure 0.14 — Boxplot of heart rate. (1) for the first phase; (2) for the second phase.

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