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Selected Methodological Approaches to Identify Functional Groups in Running

by

Stefan Hoerzer

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

GRADUATE PROGRAM IN KINESIOLOGY

CALGARY, ALBERTA

DECEMBER, 2017

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Abstract

A footwear construction typically produces different biomechanical, physiological, and/or perceptual responses for different groups of individuals. Consequently, a given insert or shoe can be beneficial for one group, but ineffective or even detrimental for another group. This observation represents a key challenge in the attempt to develop athletic footwear constructions that improve athletic performance, reduce the risk of movement-related injuries, and/or enhance comfort. A functional group is a collection of individuals with the same functional solutions when executing a locomotion task, and when reacting to a locomotion task intervention, such as footwear. It was speculated that tailoring footwear constructions to the functional solutions of these groups might help to develop footwear that promotes comfort, health, and/or performance. Before footwear constructions can be matched to functional groups, the groups have to be identified. To date, however, no systematic methodological approach exists to identify functional groups. Therefore, the main objective of this doctoral thesis was to develop and test methodological approaches that lead to the identification of functional groups in running. The first approach applied pattern recognition techniques to running kinematics in order to identify functional groups. The second approach combined footwear comfort with kinematic and muscle activity data collected during running to identify functional groups. The results showed that both tested approaches successfully identified functional groups. The main finding of this thesis is therefore that functional groups can be identified (1) by utilizing pattern recognition techniques, and (2) by isolating individuals who choose the same footwear as comfortable and excluding all individuals from this groups who do not share the same biomechanical solutions. Therefore, this PhD research provides a set of tools that can be utilized to identify functional groups in order to gain a better understanding about their specific functional solutions, biological characteristics, and footwear requirements.

Preface

The chapters listed below are based on scientific manuscripts:

Chapter 3: Hoerzer, S., von Tscharner, V., Jacob, C., & Nigg, B. M. (2015). Defining Functional Groups based on Running Kinematics using Self-Organizing Maps and Support Vector Machines. Journal of Biomechanics, 48(10), 2072-2079

Chapter 4: Hoerzer, S., Trudeau, M. B., Edwards, W. B., & Nigg, B. M. (2016). Intra-Rater Reliability of Footwear-Related Comfort Assessments. Footwear Science, 8(3), 155-163.

Chapter 5: Hoerzer, S., Mohr, M., Stefanyshyn, D. J., & Nigg, B. M. (2017). Functional Grouping in Running using Footwear Comfort. Journal of Electromyography & Kinesiology, Manuscript Prepared.

This doctoral thesis was written in a manuscript-based style. Consequently, some of the chapters and sections may include redundant information - in particular, the introduction and method sections of the chapters. Chapters 4, 5, and 6 are based on three data collection sessions (i.e., two footwear comfort assessments, one biomechanical assessment) and may share a similar study population.

Acknowledgements

This doctoral thesis would not have been possible without the significant support of several individuals. It is important for me to acknowledge and thank these people:

Dr. Benno M. Nigg, my supervisor. A simple ‘thank you’ cannot describe my gratitude for all your time and effort that you have invested to help me grow professionally and personally. You always will serve as role model for me when it comes to challenging the current status to achieve something extortionary.

Dr. W. Brent Edwards, my co-supervisor. Thank you for your valuable advice, and that your door was always open when I had questions.

Dr. Vinzenz von Tscharner, member of my supervisory committee. I admire your ambition for pushing methodological boundaries in human movement science to reveal novel insights. Thank you for sharing your interesting ideas and expertise with me.

Dr. Darren J. Stefanyshyn, member of my supervisory committee. Thank you for your continuous and valuable help, and for your open, honest, and kind way of supporting me.

Drs. Walter Herzog, Christian Jacob, John E.A. Bertram, and Gert-Peter Brüggemann. Thank you for serving on the examining committee for my candidacy exam or for my thesis defense.

Benno Nigg research group. Thank you for providing a great and supportive work environment. Specifically, I would like to thank Sandro R. Nigg, Dr. Christian Maurer, Jordyn Vienneau, Dr. Jennifer Baltich, and Maurice Mohr for their continuous support throughout the last years.

Ursula Heinz, Rosalie Kolstad, Glenda L. McNeil, John Holash, Alix Westgard, and Andrzej Stano. Thank you for your great technical and administrative support.

Dr. Bernd Friesenbichler. Thank you for the great time we had together in Calgary (including endless discussions about research, sports, and life) and your support in so many different ways.

Anton, Helga, and Florian Hörzer, my parents and brother. Thank you so much for all the tremendous support and encouragement throughout my life.

Martina, my wife. Thank you so much for your incredible support throughout this journey. Without your endless patience, understanding, and love, this would have not been possible.

For my wife, Martina

For my parents, Anton and Helga Hörzer

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List of Symbols, Abbreviations and Nomenclature

Symbol	Definition
3D	Three-Dimensional
BW	Body Weight
EMG	Electromyography
GRF	Ground Reaction Force
ICC	Intra-Class Correlation Coefficient
Hz	Hertz
kg	Kilogram
m	Meter
mm	Millimeter
MDC	Minimal Detectable Change
MVC	Maximal Voluntary Contraction
N	Newton
s	Second
SD	Standard Deviation
SOM	Self-Organizing Map
SVM	Support Vector Machine
VAS	Visual Analog Scale
°	Degree

Chapter One: Introduction

Human beings are complex biological systems. The characteristics of these biological systems are determined by genetic and environmental factors. Basic genetic and environmental factors are similar across different individuals, causing humans to have similar fundamental biological characteristics. However, certain genetic and environmental factors can also be unique, and one-of-a-kind to a specific human. As a simple example, the amount of bones in the body is similar across healthy humans, but their mechanical properties may differ depending on individual exercise or dietary habits. Consequently, although the basic biological system is similar, there can be individual variations in the biological characteristics that make each human unique.

The human locomotor system is an overdetermined mechanical system. As a result, several possibilities exist for how a specific locomotor task can be performed successfully (Kuo, 1994). Multiple degrees of freedom, combined with individual biological characteristics, results in individual functional solutions when executing a locomotion task (e.g., running) or when responding to a locomotion task intervention (e.g., footwear). In this context, individual functional solutions might be specific movement patterns when performing a locomotion task such as running (e.g., Stacoff et al., 2000b; Morio et al., 2009), or specific joint loading adaptions in response to locomotion interventions (e.g., Nigg et al., 2003b; Hinman et al., 2012).

Footwear is a commonly used locomotion task intervention. Especially in sports, shoes and insoles with various construction features have been developed to support the human body (Nigg, 2010). Running is a sport that has been of particular interest regarding such footwear developments. The high popularity of this sport is one of the reasons why advancing running footwear has been a key

objective of many sporting goods manufacturers. In fact, it has been reported that jogging is one of the favorite leisure-time activities of Canadians, with an estimated 20.8% of Canadians who participated in jogging at least once in the past 3 months (Gilmour, 2007). The high risk of running injuries is another reason why the development of athletic footwear often focuses on running. Studies have demonstrated that the frequency of running injuries ranges from 15% to 85% (Nigg et al., 2015). This high injury risk demonstrates the need for running footwear interventions that reduce the likelihood of injuries. In addition to preventing injuries, running footwear has also aimed at improving athletic performance (Roy and Stefanyshyn, 2006; Sinclair et al., 2016), or enhancing footwear comfort (Nigg, 2010; Sterzing et al., 2013).

To support the human body with footwear, shoe and insole constructions with various shape and/or material characteristics have been developed and tested (Nigg, 2010; Nigg et al., 2015). Many studies have demonstrated that different runners will respond to the same insole or shoe construction differently with respect to their biomechanics, physiology and/or perception (e.g., Bates et al., 1983; Mündermann et al., 2002; Nigg et al., 2003a, 2003b; Roy and Stefanyshyn, 2006; Sinclair et al., 2016). Such individual functional responses to a footwear construction represent a major challenge in footwear development. This is because an insole or shoe construction that has a positive effect for one runner, may be ineffective or even detrimental for another runner. Thus, in the attempt to create shoe and insole constructions that can promote performance, health, and comfort, footwear research and development has to account for inter-individual variations in how a person reacts to a given footwear.

Functional grouping may be an approach to address individual variations in the response to running footwear interventions. A functional group will be defined as follows:

A collection of individuals with the same functional solutions when executing a locomotion task and when reacting to a locomotion task intervention.

It is speculated that a functional group of runners will have similar functional solutions while running. Therefore, this group of runners will also respond to a footwear intervention in the same way. In other words, although individual variations exist in the response to footwear interventions, it is speculated that there are individuals who have similar responses and, therefore, can be grouped. Tailoring footwear constructions to the functional solutions of these groups might help to develop footwear that promotes comfort, health, and/or performance. Before footwear constructions can be matched to functional groups, the groups have to first be identified. To date, however, no systematic methodological approach exists to identify functional groups.

The main objective of this doctoral thesis was to test methodological approaches that might lead to the identification of functional groups for running footwear.

Functional groups may be identified using a number of different methods. For this thesis, however, two approaches were chosen that were assumed to be promising ways to identify functional groups based on the findings of previous studies. The first approach applied pattern recognition techniques to identify functional groups. The second approach utilized footwear comfort to identify functional groups.

1.1.1 Approach 1: Pattern Recognition Techniques

Previous research in biomechanics aiming to identify different groups utilized the following method (e.g., Ferber et al., 2003; Chumanov et al., 2008; Fukuchi and Duarte, 2008): First, subjects were pre-grouped based on selected biological characteristics (e.g., age, gender). These characteristics were assumed to cause functionally different solutions when executing a locomotion task or when reacting to a locomotion task intervention. Second, the kinematics, kinetics, and/or muscle activity patterns of these groups during locomotion were measured. Finally, the measured data of the pre-defined groups were compared using time-discrete variables. Time-discrete variables are single values at a certain point in time, such as the knee angle at the moment of heel-strike or simply the maximum value of a variable (Nigg, 2010).

This standard approach has several limitations with respect to the identification of functional groups. When pre-grouping individuals using known biological characteristics (e.g., age, gender), groups that differ because of unexpected/unknown characteristics remain undetected. Furthermore, using only time-discrete variables to compare groups ignores the majority of the collected data (Nigg, 2010; Maurer et al., 2012). As a result, data that could contain the important discriminating information to identify the groups may be ignored.

Pattern recognition techniques have been developed with the objective to identify clusters of similar data or classify data using complex, holistic data sets (Bishop, 2006). These techniques have been utilized for various applications, such as manufacturing engineering (Harding et al., 2006) and relationship management between customers and companies (Ngai et al., 2009). More importantly, in locomotion and footwear biomechanics research, these techniques have been

successfully used, for example, to investigate the biomechanical effects of different footwear constructions (Lamb et al., 2011; Nigg et al., 2012; Hoerzer et al., 2015a), or to analyze/classify sex groups (Eskofier et al., 2012; Maurer et al., 2012; Nigg et al., 2012) and age groups (Fukuchi et al., 2011; Eskofier et al., 2013). It was speculated that pattern recognition techniques have the capability to overcome the described limitations of the standard approach to identify groups (i.e., relying on pre-defined groups and time-discrete variables). Specifically, a combination of different pattern recognition techniques might allow for the identification of functional groups.

Pattern recognition techniques can be categorized into supervised and unsupervised tools. Unsupervised pattern recognition techniques were designed to automatically separate clusters of similar data. These techniques, therefore, might have the capability to separate groups with different functional solutions, without the need for pre-grouping individuals based on known biological characteristics. Following the separation of the groups, supervised pattern recognition techniques reveal the discriminating information between the separated groups. This type of information is important to match footwear constructions to different groups. Both supervised and unsupervised pattern recognition techniques can operate with holistic data sets including time-continuous variables. Hence, rather than using selected time-discrete variables, these tools use all the available data for the group identification.

Therefore, the *first project* of this thesis investigated whether pattern recognition techniques can be used to identify functional groups.

1.1.2 Approach 2: Footwear Comfort

Nigg et al. (2015, p.5) has proposed the 'comfort filter' paradigm, which states that "when selecting a running shoe, an athlete selects a comfortable product using his/her own comfort filter. This automatically reduces the injury risk and may be a possible explanation for the fact that there does not seem to have been a trend in running injury frequencies over time."

This new paradigm is based on research demonstrating that footwear comfort has a functional impact on the human body. In fact, enhanced footwear comfort has been suggested to improve running performance (Luo et al., 2009), reduce the frequency of exercise-related injuries (Mündermann et al., 2001; Kinchington et al., 2011), and may be associated with improved neuromuscular control of balance (Burke, 2012). In addition, it has been shown that different individuals select different footwear characteristics to be comfortable (Chen et al., 1994; Mündermann et al., 2001). Considering these findings about footwear comfort, one may speculate that people with the same comfort perception have (a) the same biomechanical/physiological solutions during locomotion and in response to a footwear condition, and (b) the same needs with regards to footwear constructions. Therefore, individuals that feel comfortable in the same footwear construction may form a functional group. As a result, it was speculated that footwear comfort assessments can be utilized to identify functional groups. In addition, footwear comfort assessments may also allow to identify footwear constructions that promote a functional group's health and/or performance.

This doctoral thesis investigated whether footwear comfort can be used to identify runners that belong to the same functional group. In addition, this thesis addressed the question whether

footwear comfort can also be utilized to select the right footwear construction for a functional group.

Footwear comfort is a multifactorial variable, influenced by mechanical, neurophysiological, and psychological factors (Mills et al., 2010). Combining the multifactorial nature of footwear comfort with the fact that it is measured subjectively, makes footwear comfort a variable that is difficult to quantify. Therefore, different measurement tools and protocols have been proposed to quantify footwear comfort (Mündermann et al., 2002; Mills et al., 2010). The ability of an individual to rate footwear comfort, however, has not yet been tested. Understanding the reliability of an individual in assessing footwear comfort is important as unreliable individuals might represent potential confounders when using footwear comfort to identify functional groups.

Therefore, the *second project* of this thesis tested the intra-rater reliability of footwear comfort assessments and proposed approaches to improve reliability of footwear comfort assessments.

The objective of the *third project* of this thesis was to test whether footwear comfort, combined with biomechanical assessments, can be utilized to identify functional groups with similar and group-specific functional solutions while running.

The *fourth project* of this thesis investigated a functional group's running biomechanics in the attempt to understand whether footwear comfort can be used to select footwear constructions that improve running performance and/or reduce the risk of running-related injuries.

In summary, this doctoral thesis attempted to answer the following research questions:

1) Can pattern recognition techniques be used to identify functional groups?

   In Chapter 3, a Self-Organizing Map in combination with a Support Vector Machine was used to identify functional groups with group-specific running kinematics using a data set including 88 healthy individuals.

2) How reliable are footwear-related comfort assessments?

   This question was addressed in Chapter 4. The intra-rater reliability of footwear comfort assessments of 90 healthy individuals was determined. Each study participant rated footwear comfort of six different shoe insoles after running with them.

3) Can footwear comfort be used to identify functional groups?

   Chapter 5 provided insights about this question. Out of 114 healthy individuals, a group of 18 people who felt comfortable with the same footwear condition was selected. Using lower extremity kinematics and muscle activity data, it was determined which members of this group had similar and group-specific functional solutions during running and, therefore, formed a functional group.

4) Can footwear comfort be used to select beneficial footwear for a functional group?

   This question was addressed in Chapter 6. The kinematics, kinetics, and muscle activity data of the functional group identified in Chapter 5 were investigated, while running in a comfortable and an uncomfortable footwear condition.

Chapter Two: Background

2.1 Definition of Functional Groups

Humans can have individual functional solutions when executing a locomotion task and when reacting to a locomotion task intervention. These individual functional solutions can be expressed by their biomechanics (e.g., movement pattern), their physiology (e.g., oxygen consumption), and/or their perception (e.g., comfort). Individuals whose functional solutions are similar may be assigned to a 'functional group' (Nigg, 2010). Therefore, a functional group is defined as follows:

> *A functional group is a collection of individuals with the same functional solutions when executing a locomotion task and when reacting to a locomotion task intervention.*

The objective of this background chapter is to present aspects that are important when studying functional groups. Specifically:

1. Previously documented inter-individual functional solutions regarding both locomotion tasks and locomotion task interventions (i.e., footwear),

2. Functional grouping to address individual responses to footwear,

3. The relevance of functional groups in footwear biomechanics, and

4. Considerations for identifying functional groups in footwear biomechanics.

2.2 Inter-Individual Differences in Functional Solutions

The musculoskeletal system is the foundation of locomotion. The major structural components of the human musculoskeletal system are skeletal muscles, bones, articular cartilage, ligaments, and tendons (Nigg and Herzog, 2007). The properties of these structural components are influenced by both genetic and environmental factors (e.g., Zernicke et al., 2007; Richards et al., 2012; Thomis and Aerssens, 2012). Examples of such genetic and environmental factors are heredity, physical activity, or age. The actual influence of these genetic and environmental factors on the structural components of the musculoskeletal system differs for each human. As a result, every human has individual properties with respect to her/his structural components. In addition to variations in the structural properties, genetic and environmental factors also seem to influence the ability of humans to control movement or the musculoskeletal system, respectively (Frigon, 2011, 2015).

The locomotor system of a human is an overdetermined mechanical system. Therefore, when executing a motor task such as walking or running, numerous degrees of freedom exist (Kuo, 1994). Combing this large number of movement execution possibilities and the inter-individual differences of the musculoskeletal system leads to subject-specific functional (biomechanical, physiological, and/or perceptual) solutions when performing a given motor task (Dufek et al., 1995). Specifically, individual functional solutions can be observed with respect to:

(a) a locomotion task

    This describes individual functional solutions (e.g., unique movement pattern) when executing a locomotion task (e.g., running, walking) under certain boundary conditions.

(b) an intervention to the locomotion task

This describes individual functional solutions (e.g., unique change in the movement pattern) in the reaction to an intervention (e.g., footwear) that affects the locomotion task.

2.2.1 Inter-Individual Functional Solutions During Locomotion

Bianchi et al. (1998, p. 343) has stated that "in the search for the laws that govern movement, one often concentrates on the average characteristics of performance. In this way, we neglect inter-individual variability with the implicit assumption that it mainly reflects random noise in the implementation of standard invariants, rather than actual diversity of motor strategies." While most of the studies in the field of locomotion biomechanics do, indeed, discuss only group mean values, there are several studies that have analysed and/or reported inter-individual differences in the functional solutions during a locomotion task. Such inter-individual differences will be discussed for walking and running.

For walking, inter-individual differences have been found based on kinematic and kinetic data while walking with bare feet (Bianchi et al., 1998; Revill et al., 2008). Differences in the biomechanical solutions among humans were also reported with respect to more sophisticated walking tasks, such as walking downhill, both with and without hiking poles (Schwameder et al., 1999), or walking with high-heeled dress shoes (Schöllhorn et al., 2002). Therefore, it seems that subject-specific or group-specific functional solutions while walking have been known for some time, and occur under different boundary conditions.

The majority of the research showing individual functional solutions while performing a locomotion task, however, focuses on running. In fact, already in early human movement studies, such a variability among runners was acknowledged (Fenn, 1930). The author reported variations in the kinetic energy of the lower legs among individuals during sprint running. Since this early work, several other studies have demonstrated inter-individual differences in running kinetics (Cavanagh and Lafortune, 1980; Bates et al., 1983; Oleson et al., 2005). Cavanagh and Lafortune (1980), for example, found substantial inter-individual differences in the peak values of the vertical ground reaction force. The authors stated that while running with the same speed, there could be differences of about 30% in the vertical ground reaction force (relative to body weight) between runners. In addition, inter-individual differences exist with respect to kinematic variables in running (Oleson et al., 2005; Morio et al., 2009) and with respect to the adjustment of leg stiffness when running on uneven surfaces (Grimmer et al., 2008). Running economy is another variable that has been associated with substantial variations across individuals (Williams and Cavanagh, 1987). For example, in a study by Heise and Martin (2001), the least economical runner used 83% of his VO_{2peak} while running at 3.35 ms^{-1}, compared to the most economical runner who only used 59%. Despite the variety of variables that have been shown to differ across runners, the vast majority of studies with an actual research focus on individual differences among runners were conducted in the 1980s (e.g., Bates et al., 1983; Cavanagh et al., 1985).

The subject-specific functional solutions that have been discussed in this chapter so far were detected using measurement techniques (e.g., 3D motion capture systems with markers mounted on the skin, clothes, or shoes) that do not quantify actual skeletal movements or internal loadings and, therefore, only provide an estimate for these variables (Reinschmidt et al., 1997a, 1997b).

Using such measurement techniques is a common and accepted limitation of many locomotion studies. However, considerable differences can be found in some cases between estimated and actual movement values (Reinschmidt et al., 1997a, 1997b). Thus, one may ask the question whether subject-specific biomechanical solutions have also been reported with respect to actual skeletal movements or internal loadings. In a series of studies conducted by Stacoff et al. (2000a, 2000b, 2000c), skeletal movements of the tibia and calcaneus were measured during the stance phase of running using bone-pins. By investigating five healthy male individuals, the authors reported inter-individual differences in the running patterns. Internal joint loadings of the knee and hip joint have also been investigated using instrumented joint implants. Subject/patient-specific loading profiles have been found in these studies while performing daily activities (Bergmann et al., 2001; Kutzner et al., 2010). Overall, the measurements of actual, internal skeletal movements and joint loadings further support the previous findings that show individual variations in the functional solutions while performing various locomotion tasks.

In summary, inter-individual differences in the functional solutions when executing a locomotion task have been observed in several studies. Yet, it is important to note that the basic pattern of the functional solutions (e.g., the gross movement pattern) seems to remain similar across healthy individuals. A human being, however, can have certain alterations to this gross pattern that makes his/her style of locomotion unique.

2.2.2 Individual Functional Solutions in Response to a Locomotion Task Intervention

It is well known that footwear interventions such as inserts or shoes can influence human locomotion (Frederick, 1986). Therefore, footwear interventions have been frequently used as a

way to modify locomotion. The objective of footwear is often to influence/change human movement to prevent injuries, enhance comfort, and/or increase performance. Bates et al. (1983, p. 182), however, has emphasized that "since individuals are anatomically and functionally different, it seems reasonable to suspect that runners might respond differently to various types of shoes". This means, one can speculate that humans have subject-specific biomechanical, physiological, and/or perceptual reactions to footwear interventions.

Footwear interventions often aim to benefit the human musculoskeletal system. However, since humans can respond individually to identical footwear constructions, not all individuals react in a beneficial and/or expected manner. Individuals with a beneficial and/or expected functional response to a footwear intervention have been referred to as 'responders', whereas the remaining individuals are termed 'non-responders' (Hinman et al., 2012; Madden et al., 2016). Groups of responders and non-responders to footwear interventions - or simply groups of individuals that have different reactions to the same footwear intervention - have been repeatedly revealed in footwear-related studies and will be discussed in the following sections.

2.2.2.1 Inserts

Shoe inserts (and orthotics) have been developed and utilized for various functional objectives. According to Nigg (2010), the purpose of an insert can be to align the skeleton, to provide guidance and control for foot and leg movement, to improve the damping of impact forces, to improve sensory feedback, to improve comfort, and to reduce the frequency of injuries. As it will be demonstrated below, identical inserts can lead to diverse and sometimes unexpected/undesirable reactions across individuals.

One of the most important functional objectives of inserts is to align the skeleton and/or to control movement (Nigg et al., 1999; Nigg, 2010). To this end, inserts with different shape modifications, such as medial or lateral wedges (Nester et al., 2003; Nigg et al., 2003b; Kakihana et al., 2007; Hinman et al., 2008, 2012; Lewinson et al., 2013) and arch supports (Stacoff et al., 2000c) have been developed. Such shape modifications have been suggested to decrease joint loading, and therefore reduce discomfort and pain of individuals with knee osteoarthritis (Kakihana et al., 2007; Hinman et al., 2008, 2012) and patellofemoral pain (Lewinson et al., 2013). The biomechanical mechanisms of these shape modifications appear to be rather simple. According to Hinman et al. (2012), lateral wedges, for example, cause a center of pressure shift in lateral direction. This shift in combination with a more vertically aligned ground reaction force vector, reduces the lever arm between knee and ground reaction force vector, and therefore reduces knee moment and loading. Given this simple mechanism, it is surprising that numerous studies have shown that laterally or medially placed wedges do not produce the same reactions for all individuals (Nester et al., 2003; Nigg et al., 2003b; Kakihana et al., 2007; Hinman et al., 2008, 2012; Lewinson et al., 2013). Nigg et al. (2003b), for example, demonstrated that the maximal knee abduction moment increased for nine and decreased for six individuals while running with the same wedged insert construction. Hinman et al. (2012) found inter-individual differences in the peak knee adduction moment in a sample of 73 individuals. In this study, a substantial amount of the participants (23%) had an unexpected and potentially detrimental reaction (i.e., increased knee adduction moment) to the laterally wedged insoles. By using bone-pins to measure actual skeletal movements Stacoff et al. (2000c) also found individual movement responses of the calcaneus and tibia to inserts with arch support during running.

Next to shape modifications, shoe inserts with altered material properties have also been used to control the movement of the lower extremities. Nigg and colleagues (1998), for example, studied five insert constructions with different material properties developed to reduce foot eversion and tibial rotation. The authors found that the subjects reacted differently to the same insert while running. Three out of the twelve subjects showed an increase in total tibial rotation, while six subjects showed a decrease. Interestingly, for some subjects the functional response to the insert could be predicted based on biological characteristics, such as a stiff or flexible foot arch. Overall, a given insert that was designed to align the skeleton or control the movement can lead to unexpected results. In fact, for some of the aforementioned studies, the percentage of non-responders to the tested insert conditions can be calculated: 13% (Hinman et al., 2008), 0-18% (Kakihana et al., 2007), 23% (Hinman et al., 2012), 20-60% (Stacoff et al., 2000c), and 50-83% (Nigg et al., 1998).

Shoe inserts do not only affect a person's biomechanics, but they can also impact the sensory system. Nurse et al. (2005) studied insole induced changes to the afferent feedback during walking. The authors reported that changing the texture of the insoles resulted in subject-specific adaptions to the walking pattern measured using kinetic, kinematic, and muscle activity data.

Enhancing footwear comfort is another important functional objective of shoe inserts. Shape modifications such as wedges (Mündermann et al., 2002, 2003), low and high arches (Mündermann et al., 2001), flat and spherical heel areas (Chen et al., 1994; Mündermann et al., 2001), and prefabricated or custom-molded designs (Mündermann et al., 2003, 2004; Mills et al., 2012) have been used to influence footwear comfort. Materials with different hardness (Chen et

al., 1994; Mündermann et al., 2001, 2002; Mills et al., 2012) and elasticity (Mündermann et al., 2001) properties were also used to enhance footwear comfort. Different individuals can perceive a given shoe insert differently (Chen et al., 1994). Therefore, in several studies investigating the effect of inserts on footwear comfort, subject-specific responses have been observed (Chen et al., 1994; Mündermann et al., 2001, 2002, 2003; Mills et al., 2012). The calculated percentage of non-responders (i.e., comfort was not improved) in two of these studies was: ~15-65% (Mündermann et al., 2003), and 85-96% (Mündermann et al., 2001).

In summary, shoe inserts have various shape, material and surface characteristics, which have been developed for different functional objectives. Some individuals react to an insert/orthotic in an unexpected manner such that the desired objective is not achieved. Especially for footwear comfort, substantial variations in the response to a given insert condition can be seen (i.e., more than 80% non-responders in some cases). Overall, it appears that a “one fits all” solution cannot be used to select insert constructions for an individual and instead, there is substantial variability in the functional solutions in the response to these footwear interventions (Table 2-1).

Table 2-1: Summary of studies with individual functional solutions in response to shoe inserts/orthotics (sorted by insert objective and reference date). Where possible, the percentage of responders (R) and non-responders (NR) was calculated. Responders were defined as individuals who demonstrated an expected and/or beneficial functional response to the insert. In cases where it could not be determined whether the response was expected and/or beneficial, the sizes (in %) of the groups (G1, G2, etc.) with group-specific responses were determined.

Insert Objective	Reference	Feature	Sample Size	Group Sizes	Task
Comfort	(Chen et al., 1994)	Shape, Hardness, Thickness, and Flexibility	14	Could not be calculated	Walking and Running
Comfort	(Mündermann et al., 2001)	Shape, Hardness, and Elasticity	103	R: 4-25% NR: 85-96%	Military Activities
Comfort	(Mündermann et al., 2002)	Shape and Hardness	9	Could not be calculated	Running
Comfort	(Mündermann et al., 2003)	Shape	20	N: ~35-85% NR: ~15-65%	Running
Comfort	(Mills et al., 2012)	Shape and Hardness	40	Could not be calculated	Running
Movement Control	(Nigg et al., 1998)	(Vertical) Dual Density Midsole	12	R: 17-50% NR: 50-83%	Running
Movement Control	(Stacoff et al., 2000c)	Arch Support	5	R: 40-80% NR: 20-60%	Running
Movement Control	(Nurse et al., 2005)	Surface Texture	15	G1: 67-93% G2: 7-33%	Walking

Movement Control and Skeletal Alignment	(Nester et al., 2003)	Lateral and Medial Wedge	15	Could not be calculated	Walking
Skeletal Alignment (Joint Loading)	(Kakihana et al., 2007)	Lateral Wedge	51	R: 82-100% NR: 0-18%	Walking
Skeletal Alignment (Joint Loading)	(Hinman et al., 2008)	Lateral Wedge	40	R: 88% NR: 13%	Walking
Skeletal Alignment (Joint Loading)	(Hinman et al., 2012)	Lateral Wedge	73	R: 77% NR: 23%	Walking
Skeletal Alignment (Joint Loading)	(Lewinson et al., 2013)	Lateral and Medial Wedge	9	G1: 56-78% G2: 22-44%	Running
Skeletal Alignment	(Nigg et al., 2003b)	Lateral and Medial Wedge	15	G1:13-60% G2: 40-87%	Running

2.2.2.2 Shoes

The field of biomechanics of running shoes started to emerge in the 1970s. In these early years, an important objective of running shoes was to reduce impact forces that occur during the stance phase of running. These forces were assumed to cause running injuries (Nigg, 2010). Multiple studies have investigated the influence of shoes with different cushioning properties on the vertical ground reaction force during running (Frederick, 1986). In a review article, Frederick (1986, p. 171) pointed out that researchers (Bates et al., 1983; Clarke et al., 1983a, 1983b) "…have suggested that the contradictory results often seen in these experiments may be, in part, due to the pronounced inter-individual differences in the response to various shoes…". Bates et al. (1983),

for example, showed variations in the ground reaction force response to different running shoes among individuals.

Subject-specific functional solutions in response to shoes have also been documented with respect to athletic performance. Several studies reported that a given footwear construction can improve performance for some athletes, but has no effect or reduces performance for others (Nigg et al., 2003a; Roy and Stefanyshyn, 2006; Tung et al., 2014; Madden et al., 2016; Sinclair et al., 2016). Tung et al. (2014), for example, reported inter-individual differences in the metabolic cost when running on surfaces with different cushioning properties. The outcome of this study suggested that individuals have different cushioning requirements to optimize their running performance/economy. Nigg et al. (2003a) investigated two shoes, an elastic heel and a visco-elastic heel model, with respect to muscle activation and energy aspects and identified three groups: subjects who performed best with the elastic condition, subjects who performed best with the visco-elastic feature, and subjects with no clear effect. The need for subject-specific footwear constructions to optimize athletic performance has also been demonstrated with respect to shoe bending stiffness (Roy and Stefanyshyn, 2006; Madden et al., 2016) and midsole materials with different elasticity properties (Sinclair et al., 2016). In these studies, 15% (Roy and Stefanyshyn, 2006), 17-25% (Sinclair et al., 2016), 33-42% (Tung et al., 2014), and 44% (Nigg et al., 2003a; Madden et al., 2016) of the participants were non-responders.

Recently, barefoot running and its unique characteristics has become of interest for running biomechanics research (Nigg and Enders, 2013). It has been shown that subject-specific functional solutions can be expected when changing between barefoot and shod running (De Wit et al., 2000;

Stacoff et al., 2000a; Morio et al., 2009; Hoerzer et al., 2015a). De Wit et al. (2000), for example, studied the functional adaptions between running barefoot and running with shoes for different speeds. The authors reported similar kinematic adaptions in the sagittal plane of motion within the tested runner cohort. However, frontal plane kinematics (especially at the foot and ankle) seemed to be more subject-dependent. De Wit et al. (2000, p. 277) tried to explain this observation by speculating that "…the frontal plane kinematics are influenced by the individual anatomy of the foot-ankle." Subject-specific adaptions between running with bare feet to running with shoes were also found by Hoerzer et al. (2015a). In this study, a gait asymmetry index was developed using kinematic and kinetic variables. For most of the tested individuals, wearing footwear decreased gait asymmetry compared to the barefoot condition, whereas for three out of the 15 participants gait asymmetry was increased.

Subject-specific responses to athletic shoes have also been demonstrated in sports other than running. In sprinting, inter-individual differences in the athletic performance of athletes were observed with respect to sprint spikes with different sole bending stiffness properties (Stefanyshyn and Fusco, 2004). The authors reported that 15% of the study participants did not improve performance with a stiff plate condition. These subject-dependent requirements in plate stiffness properties could not be explained with body mass, body height, shoe size, or skill-level of the athletes. Stefanyshyn and Fusco (2004, p.55) speculated that "…individual differences in the force-length and force-velocity relationships of the calf muscles may influence the appropriate shoes stiffness for each athlete to obtain their maximal performance." Hreljac (1998) tried to identify the "best" tennis shoe for each of three different athletes based on kinematic and kinetic data collected during lateral movements. The author found differences among the athletes in their

response to these sport shoes, which differed in the midsole densities. Dufek and Bates (1991) found subject-specific responses to different types of sport shoes (i.e., basketball, volleyball, and running shoes) in the attenuation of impact forces during hanging drop landings.

Sport shoes commonly have a functional objective, such as improving athletic performance or reducing the risk of movement-related injuries. Shoes with a functional objective, however, have also been developed for activities of daily living. Similar to sport shoes, studies have shown that individuals can react differently to this type of footwear (Erhart et al., 2008, 2010; Kutzner et al., 2011). For example, Erhart et al. (2008) investigated whether a variable-stiffness shoe (1.3-1.5 times stiffer on the lateral side) could reduce knee adduction moments in a cohort of 79 patients with symptoms of medial compartment knee osteoarthritis. The effect of this variable-stiffness construction was subject-dependent. The majority of the study participants experienced the desired reduction in the peak knee adduction moment (compared to a control shoe). However, a considerable amount of the patients (n=14) demonstrated an unexpected increase in peak knee adduction moment. These instantaneous patient-specific responses in knee joint loading were further confirmed by a longitudinal study on the effects of the variable-stiffness shoe by the same research group (Erhart et al., 2010). After six months of wearing the variable-stiffness shoe, five of 34 patients had an increase in the knee joint loading. In a different study, Kutzner et al. (2011) found inter-individual differences in the knee medial compartment load response to laterally wedged shoes using instrumented knee implants. While for some of the study participants no reduction in knee joint loadings was found, other individuals had a load reduction of up to 15%. The percentage of non-responders to functional footwear used for daily activities was 18% (Erhart et al., 2008), 15-32% (Erhart et al., 2010), and 33% (Kutzner et al., 2011).

In the previous section, it has been demonstrated that different individuals select different insoles to be comfortable. Such inter-individual differences in the perceptual response have also been shown with respect to shoes (Miller et al., 2000; Wegener et al., 2008). Wegener et al. (2008), for example, tested two running shoes and 18 participants selected one running shoe model as most comfortable, while 3 subjects chose the other shoe to be most comfortable.

Functional solutions in response to shoe interventions show subject-specific variations (Table 2-2). Although these subject-specific differences are commonly observed for running shoes, it is apparent that this phenomenon is also present for other sport shoes and for shoes used for daily activities.

Table 2-2: Summary of studies with individual functional solutions in response to shoes (sorted by shoe objective and reference date). Where possible, the percentage of responders (R) and non-responders (NR) was calculated. Responders were defined as individuals who demonstrated an expected and/or beneficial functional response to the tested shoe condition. In cases where it could not be determined whether the response was expected and/or beneficial, the sizes (in %) of the groups (G1, G2, etc.) with group-specific responses were determined.

Shoe Objective	Reference	Feature	Sample Size	Group Sizes	Task
Comfort	(Miller et al., 2000)	Athletic Court Shoes	18	Could not be calculated	Standing, Waking, and Running

Comfort	(Wegener et al., 2008)	Running and Street Shoes	22	R: 18-86% NR: 14-82%	Running and Walking
Cushioning	(Dufek and Bates, 1991)	Different Sport Shoes	5	Could not be calculated	Drop Landing
Cushioning & Stability	(Bates et al., 1983)	Not Specified	5	Could not be calculated	Running
Joint Loading	(Erhart et al., 2008)	Increased Lateral Stiffness	79	R: 82% NR: 18%	Walking
Joint Loading	(Erhart et al., 2010)	Increased Lateral Stiffness	34	R: 68-85% NR: 15-32%	Walking
Joint Loading	(Kutzner et al., 2011)	Lateral Wedge	6	R: 67% NR: 33%	Walking
Performance	(Nigg et al., 2003a)	Heel Midsole Elasticity and Hardness	18	R1: 28% R2: 28% NR: 44%	Running
Performance	(Stefanyshyn and Fusco, 2004)	Bending Stiffness	34	R: 85% NR: 15%	Sprinting
Performance	(Roy and Stefanyshyn, 2006)	Bending Stiffness	13	R: 85% NR: 15%	Running
Performance	(Tung et al., 2014)	Cushioning Thickness	12	R: 58-67% NR: 42-33%	Running
Performance	(Madden et al., 2016)	Bending Stiffness	18	R: 56% NR: 44%	Running
Performance and Comfort	(Sinclair et al., 2016)	Midsole Elasticity	12	Performance: R: 75-83% NR: 17-25% Comfort: R: 42% NR: 58%	Running

Performance and Injury	(Hreljac, 1998)	Midsole Hardness	3	Could not be calculated	Lateral Movements
Shod Running	(De Wit et al., 2000)	-	9	G1~67-100% G2: ~0-33%	Running
Shod Running	(Stacoff et al., 2000a)	-	5	G1: 40% G2: 40% G3: 20%	Running
Shod Running	(Morio et al., 2009)	-	10	G1: 70-80% G2: 20-30%	Running
Shod Running	(Hoerzer et al., 2015a)	-	15	R: 80% NR: 20%	Running

2.3 Functional Groups to Address Individual Functional Solutions

Experiments in the field of locomotion and footwear biomechanics rely often heavily on group statistics. Devita and Skelly (1990, p. 99) described this situation as "typically most studies have employed one or more homogeneous subject groups and presented data describing the average performance of groups in various experimental conditions". Using group statistics has two major advantages. First, larger sample sizes can be investigated, which leads to an increased statistical power for a study (Lachin, 1981). These larger sample sizes can be achieved because increasing the number of study participants is often more feasible than increasing the number of trials (e.g., risk of inducing fatigue). Second, group statistics are based on the idea of testing a sample to make conclusions about a population (Bates, 1996; James and Bates, 1997). This improves the generalizability of the study findings and, therefore, the relevance of the conducted study.

As demonstrated in this chapter, human beings illustrate individual biomechanical, physiological, and/or perceptual responses to a locomotion task and to a footwear intervention. In addition, it is very likely that many more studies in locomotion and footwear biomechanics identified such subject-specific functional solutions, but neglected these subject-specific data by focusing on group mean values. Such subject-dependent functional solutions might even exist within presumably homogeneous groups (e.g., within a group of healthy male athletes, within a group of elderly females, etc.). Group statistics using mean data has limitations when dealing with these subject-specific functional solutions. Averaging the movement pattern of a group of individuals, for example, might result in an average movement pattern that does not reflect the true movement pattern of any individual in the subject group (Devita and Skelly, 1990; Bates, 1996). Importantly, averaging different functional solutions of multiple individuals may also result in false conclusions

with respect to the effect of a tested intervention (e.g., footwear) (James and Bates, 1997; Kanai and Rees, 2011). If some study participants show negative while others have positive responses, these inter-individual differences might cancel each other out in the calculated average (James and Bates, 1997; James et al., 2003). In this context, James et al. (2003, p. 117) have noted that "in research aimed at improving health or performance, an important treatment, perturbation, or risk factor could be overlooked because of an incorrect conclusion resulting from this cancelation effect". Therefore, research strategies have been proposed to account for the limitations associated with group statistics. These strategies might be categorised into 'single-subject' and 'functional group' approaches.

2.3.1 Single-Subject Approach

Studies utilizing the single-subject approach focus the data analysis, interpretation, and discussion on the individual (James and Bates, 1997). Bates (1996) was likely the first to propose the single-subject approach for human movement studies. Hreljac (1998) acknowledged the value of this approach by studying the specific response of individuals to athletic shoes. Limitations of the single-subject approach include the generalizability of the study findings and its impracticability when aiming for large sample sizes.

2.3.2 Functional Group Approach

The functional group approach clusters individuals with similar functional solutions when performing a locomotor task or when reacting to a locomotor task intervention. In this way, functional grouping combines the advantages of both the single-subject approach and group statistics. First, grouping people with the same functional solutions limits the risk of obtaining (a)

an average response that does not represent any of the tested individuals, and (b) a cancellation effect of negative and positive responses. Second, including a group of people allows for large sample sizes with increased generalizability and statistical power. Hence, the concept of functional groups, which was utilized in this doctoral thesis, has its foundation in the need to account for subject-dependent functional solutions in locomotion and footwear biomechanics research.

The terminology and definition of functional groups has primarily been proposed and advocated in the work published by Nigg et al. (1999) and Nigg (2010). Although often not referred to as a functional group, research can be found that describe groups of individuals with similar functional solutions. In a very general sense, functional groups could be defined by comparing healthy versus injured individuals. However, this thesis and literature review focuses on functional groups within healthy individuals.

In locomotion biomechanics, (functional) groups have been studied showing age-specific (Begg and Kamruzzaman, 2005; Fukuchi and Duarte, 2008), sex-specific (Ferber et al., 2003; Maurer et al., 2012), and anthropometric-specific (Nawoczenski et al., 1998; Williams III et al., 2001) solutions during locomotion. In addition to grouping people based on musculoskeletal characteristics, other studies defined groups based on center of pressure patterns (Cavanagh and Lafortune, 1980), impact forces (Bahlsen, 1989), foot posture (Nielsen et al., 2014), running patterns (Phinyomark et al., 2015), running economy (Williams and Cavanagh, 1987), or similar free moments (or frictional torques) of ground reaction during running (Willwacher et al., 2016). Until today, perhaps the most comprehensive and systematic research aiming to identify and study individuals or groups with group-specific functional solutions to locomotion or other motor tasks

has been conducted by Bates and co-workers (e.g., Caster and Bates, 1995; Dufek et al., 1995; Bates, 1996; James et al., 2003, 2014). In this line of work, individuals have been studied based on the ground reaction force response to different locomotion and motor tasks. James et al. (2014), for example, proposed five (functional) groups with suggested differences in the load accommodation strategies to an external weight, such as 'Super-Newtonian' (i.e., ground reaction force increases more than added external weight), 'Newtonian' (i.e., ground reaction force increase is similar to the added external weight), and "Negative Biomechanical" (i.e., ground reaction force decreased with added external weight).

Functional grouping has already been utilized in some studies focusing on locomotion and other motor tasks. However, given the well-known inter-individual differences in response to footwear, it is surprising that there are only a few studies that specifically focused on group-specific responses to footwear constructions. Nigg et al. (2003a), for example, identified two (functional) groups with group-specific responses to footwear with different material properties. Madden and co-workers (2016) identified and investigated two groups of runners. Each group required a specific forefoot bending stiffness to optimize their running economy. Mündermann et al. (2001) grouped people with similar comfort perceptions to different insole constructions. Importantly, these authors showed that providing each functional group a group-specific insole solution reduced the frequency of movement-related injuries. In summary, there is a paucity (especially in footwear biomechanics) of research that has focused on functional grouping.

2.4 Relevance of Functional Groups in Footwear Biomechanics

One of the key objectives of footwear biomechanics research is to develop and study footwear constructions that promote health, performance, and/or comfort in humans. This section aims to provide an understanding how subject-specific responses to footwear influences this attempt to develop inserts and shoes that benefit people. Therefore, some of the aforementioned literature will be discussed again with the specific objective to highlight subject-dependent responses in key variables that can be linked to health, performance, and comfort.

2.4.1 Health

Footwear interventions have been developed with the objective to reduce knee joint loading and, therefore, to improve knee function and health. In 2012, Hinman et al. studied laterally wedged insoles and demonstrated that 77% of the study participants showed a reduction in the knee joint loading with the test insoles, whereas the remaining individuals experienced a joint load increase. This is important since Miyazaki et al. (2002) has suggested that (based on a logistic regression analysis) a 1% increase in this type of knee joint loading (i.e., knee adduction moment) leads to a 6.46-time increase in the likelihood of knee osteoarthritis progression. Thus, the group of subjects with increased knee joint loading had a presumably detrimental response to the tested footwear feature, potentially jeopardizing knee function and health. Several other studies have demonstrated beneficial responses for one group (67-88% of the tested subjects/patients) and potentially detrimental (or no) effects for the remaining subjects with respect to joint loading (Kakihana et al., 2007; Erhart et al., 2008, 2010, Hinman et al., 2008, 2012; Kutzner et al., 2011). These studies suggest that there are groups of people that require different footwear solutions to promote health. This statement is supported by a study from Mündermann et al (2001), where different groups of

people with different footwear requirements were defined using footwear comfort. Providing each group with its group-specific footwear solution resulted in a reduction in the number of stress fractures and pain by 1.5 to 13.4%.

2.4.2 Performance

In a study by Tung and colleagues (2014), the influence of different cushioning thickness properties on the metabolic cost during running was investigated. It could be seen that there was one group of runners (about 60%) that performed better with increased cushioning thickness, while another group had a decreased running performance (i.e., increased metabolic cost). Groups with either beneficial or adverse metabolic response to the same footwear feature during running were also found by other research (Nigg et al., 2003a; Roy and Stefanyshyn, 2006; Madden et al., 2016; Sinclair et al., 2016). In a study by Stefanyshyn and Fusco (2004), different groups of sprinters were identified that required group-specific shoe stiffness properties to optimize their sprinting performance (i.e., sprinting time). In fact, 9% of the study participants had a reduced sprinting performance with increased shoe bending stiffness. The presented research emphasizes the need for subject-specific footwear properties to improve performance.

2.4.3 Comfort

Whether or not an individual perceives a footwear product as comfortable or uncomfortable is determined by footwear characteristics such as fit, torsional stiffness, cushioning, support, and stability (Nigg et al., 1999; Miller et al., 2000; Reinschmidt and Nigg, 2000; Mündermann et al., 2001; Mills et al., 2010). In addition, whether a given footwear feature feels comfortable is also related to certain properties of the musculoskeletal system, such as anthropometry, skeletal

alignment, foot sensitivity, and plantar pressure patterns (Chen et al., 1995; Miller et al., 2000; Mündermann et al., 2001). Therefore, people, who have different musculoskeletal properties can perceive the comfort of a given footwear product differently. Individuals, therefore, require different footwear solutions to improve comfort. Mündermann et al. (2001), for example, reported seven groups of people with different footwear/insole requirements to optimize footwear comfort. The tested insoles had differences in shape, hardness, and elasticity. Groups of individuals with group-specific footwear requirements for improving comfort were also found in several other studies (Chen et al., 1994; Miller et al., 2000; Mündermann et al., 2002, 2003; Wegener et al., 2008; Mills et al., 2012).

In summary, subject-specific footwear solutions can lead to the scenario that a footwear feature promotes health, performance, and/or comfort for one group of people, but has no beneficial effect, or even a detrimental outcome for another. It is therefore crucial that footwear biomechanics research accounts for subject-specific functional solutions. This may be done by identifying functional groups.

2.5 Considerations for Identifying Functional Groups in Footwear Biomechanics

As demonstrated in this chapter, different individuals can react to an identical footwear intervention quite differently, potentially causing beneficial, but also detrimental outcomes. It is speculated that tailoring footwear constructions to different functional groups might help to overcome this limitation. However, before footwear constructions can be customized to functional groups, first these groups have to be identified. Currently, there is little knowledge about the analytical and methodological approaches necessary to identify functional groups. Therefore, the need for approaches to identify functional groups is apparent.

Humans can have inter-individual differences with respect to the properties and control of the musculoskeletal system. These musculoskeletal differences might cause subject-specific biomechanical, physiological, and/or perceptual solutions when using footwear interventions (Figure 2-1). Given the proposed relationship between group-specific musculoskeletal characteristics and group-specific functional solutions, a functional group could be identified on two different levels:

(a) musculoskeletal level:

A functional group can be identified by grouping individuals with similar musculoskeletal characteristics.

(b) functional solution level:

A functional group can be identified by grouping individuals with similar functional solutions.

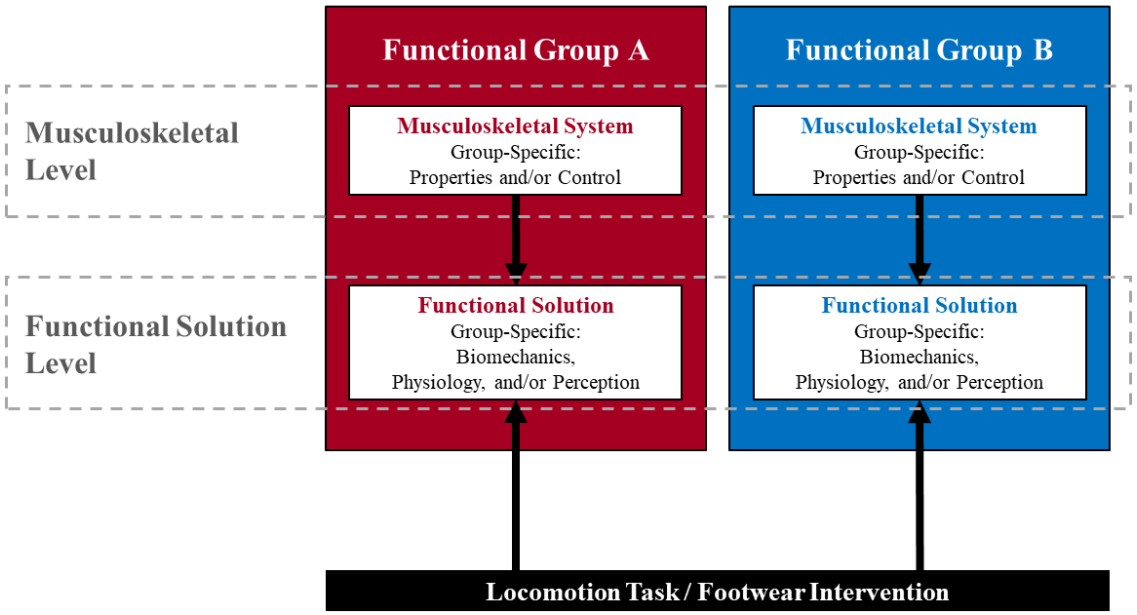


Figure 2-1: Schematic demonstrating the proposed relationship between the musculoskeletal system and functional solutions in the identification of functional groups.

Identifying functional groups based on similar musculoskeletal characteristics represents a major challenge. Little is known about which musculoskeletal characteristics cause which solutions/responses with respect to footwear interventions. Moreover, even if knowledge existed about specific musculoskeletal characteristics that cause certain reactions to footwear, it likely would be difficult to measure these characteristics (e.g., muscle composition, bone mineral density). This doctoral thesis focused therefore on identifying functional groups based on similar functional solutions. Two approaches were investigated based on (1) pattern recognition techniques and (2) footwear comfort.

2.6 Summary

Footwear biomechanics research has provided substantial evidence demonstrating that one footwear construction can result in different outcomes between individuals. Some of these reactions have been shown to be beneficial, while some are speculated to be detrimental. This represents a major challenge for footwear research and development. It was proposed that identifying functional groups will help to overcome this challenge and, therefore, is highly relevant in footwear biomechanics. In fact, it is speculated that matching footwear constructions to the group-specific musculoskeletal characteristics and/or functional solutions of functional groups will:

(a) prevent potential harmful effects of footwear interventions

(b) facilitate beneficial effects of footwear interventions

In order to be able to customize footwear constructions to functional groups, the groups first have to be identified. Currently no systematic methodological approach is available to identify functional groups. Focusing on running footwear, this doctoral thesis provides possible approaches to identify functional groups in footwear biomechanics.

Chapter Three: Identifying Functional Groups based on Running Kinematics using Self-Organizing Maps and Support Vector Machines

3.1 Introduction

A frequent goal in the field of biomechanics is to predict the "right" intervention (e.g., footwear) for a given individual. This task sounds almost trivial and has high relevance in the practical world. Many biomechanical studies have shown that individuals respond to a given intervention in a subject-dependent way with the result that the very same intervention can be beneficial for one person but not for another. Subject-dependent responses were reported with respect to footwear (Erhart et al., 2008), running surfaces (Tung et al., 2014), orthotics (Nester et al., 2003), and loading perturbations (James et al., 2014). Thus, from an analytical point of view, the task of predicting the "right" intervention is all but trivial. This paper describes the concept of functional groups and a methodological approach to identify them, which may help to overcome this challenge. Although this concept and methodological approach are presented in the context of footwear and running, they may be applied to other interventions and/or tasks.

Individuals whose responses are similar can be grouped and represent a functional group (Nigg, 2010). Matching footwear features to a functional group might enhance footwear-related comfort and improve running performance (Luo et al., 2009; Nigg, 2010). Although controversially discussed, such customized footwear may also decrease the risk of movement-related injuries (Mündermann et al., 2001; Nigg, 2010; Yeung et al., 2011).

The group-specific responses of a functional group might be the result of group-specific characteristics (e.g. similar anthropometric features). For example, previous studies have shown

that footwear-related comfort preferences are influenced by anthropometry (Miller et al., 2000; Mündermann et al., 2001). Characteristics such as age (Begg and Kamruzzaman, 2005), gender (Maurer et al., 2012), and anthropometry (Nawoczenski et al., 1998; Williams III et al., 2001) are reflected in movement patterns during locomotion. Consequently, individuals with similar characteristics are expected to have a similar inherent movement pattern. Therefore, it is hypothesized that

(1) Functional groups have group-specific footwear requirements.

(2) Functional groups have group-specific characteristics.

(3) Functional groups can be identified based on their distinctive movement patterns.

To match footwear features to a functional group, one has to first identify the different groups. This can be done using the following analytical steps: (a) *separation* of groups with significantly different movement patterns, (b) *determining* the differences between the movement patterns, and (c) *functional interpretation* of the movement pattern differences.

Previous studies aiming to separate groups with different movement patterns first pre-grouped individuals based on arbitrarily selected characteristics that were assumed to cause different movements. Age and gender were frequently used for pre-grouping individuals (Begg and Kamruzzaman, 2005; Fukuchi et al., 2011; Eskofier et al., 2012). Afterwards, the movement patterns were compared across these predefined groups to determine if there were differences. Using this approach, group-specific movement patterns caused by unknown characteristics remain undetected. In this study, unsupervised pattern recognition tools will be used that can automatically

separate groups possessing different movement patterns. This is particularly beneficial when attempting to identify functional groups where pre-grouping is not possible as the characteristics causing the group-specific movement patterns are unknown. Self-Organizing Maps (SOM) are artificial neural networks that project high-dimensional data on a low-dimensional grid in a structured fashion through unsupervised learning (Kohonen, 2001). SOMs have been successfully used to separate movements altered by different footwear modifications (Schöllhorn et al., 2002; Lamb et al., 2011), and different states of physical exhaustion (Janssen et al., 2011). It is expected that SOMs can separate groups with significantly different movement patterns and, therefore, can be used as the first step to identify functional groups. However, SOMs do not provide information about the movement differences between groups that would allow a functional interpretation. Support Vector Machines (SVMs), a supervised pattern recognition technique, have the capability to determine the actual differences across groups. SVMs were used to reveal movement and/or muscle activity pattern differences between groups of young and elderly (Eskofier et al., 2013), males and females (Maurer et al., 2012), and injured and non-injured individuals (Lai et al., 2009).

Thus, the main study objective was to propose and apply a methodological approach to identify functional groups, which included Self-Organizing Maps to separate groups with different movement patterns, and Support Vector Machines to determine and functionally interpret the movement pattern differences between the groups. Further objectives were to determine group differences in age and gender to investigate whether the functional groups could be explained by these common characteristics to predefine groups, and to investigate footwear-related comfort preferences to understand whether the identified groups required group-specific footwear features.

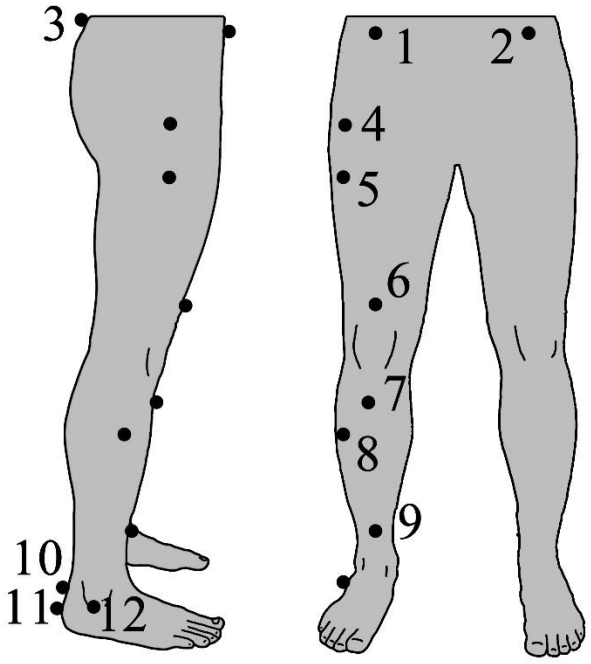
3.2 Methods

3.2.1 Data Collection

Data of 88 healthy subjects (age range: 16–76 years; 45 males, 43 females) were used in this study. The kinematic data collection of this study has been described elsewhere (Nigg et al., 2012). Kinematic data of the right lower extremity during the stance phase of heel–toe over-ground running ($3.33 \pm 0.16\ ms^{-1}$) were recorded using a marker-based 3D motion capture system (Motion Analysis Corp., USA). Subjects were equipped with 12 skin-mounted retro-reflective markers. Three markers were attached to each of four body segments (Figure 3-1a): pelvis (right/left anterior superior iliac spine; lower back), thigh (proximal, medial, and distal), shank (proximal, medial, and distal), and shoe (high/low heel and lateral aspect of the rear foot).

In this study, only the five running trials performed with the running shoe with the medium midsole hardness (Asker C-52) were analysed. The stance phase of the right leg was determined using a force platform (Kistler Instrumente AG, Switzerland) with a threshold of 20 N (sampling rate: 2400 Hz).

Comfort was assessed with respect to three running shoes that differed only in the midsole hardness: soft (Asker C-40), medium (Asker C-52), and hard midsole (Asker C-65). To assess comfort, the subjects performed at least five over-ground running trials (30 m each) for each footwear condition. Following each footwear condition, subjects were asked to rate the footwear's comfort using 130 mm Visual Analog Scales (VAS) with endpoints “not comfortable at all” (=0 comfort points) to “the most comfortable condition imaginable” (=10 comfort points).



(a)

		Marker 1			Marker …			Marker 12		
Subj.	**Trial**	$x_1 \ldots x_{101}$	$y_1 \ldots y_{101}$	$z_1 \ldots z_{101}$	…	…	…	…	…	…
1	**1**	**Matrix Dimension: 440 Rows x 3636 Columns** **440** = 88 Subjects x 5 Trials **3636** = 12 Markers x 3 Dimensions x 101 Data Points								
	2									
	3									
	4									
	5									
…	**…**									
88	**…**									

(b)

Figure 3-1: (a) Marker (black dots) setup used in this study: Marker 1–2 = right and left anterior superior iliac spine; 3 = lower back; 4–6 = right proximal, medial, and distal thigh; 7–9 = right proximal, medial, and distal shank; 10–12 = high, low and lateral shoe. (b) Structure of the input matrix (x represented the anterior–posterior, y the medio-lateral, and z the vertical direction of the

running movement). Each row was a multidimensional data vector containing the movement pattern of one subject for one running trial.

3.2.2 Data Pre-Processing

The 3D trajectories of the 12 markers for each running trial were reconstructed using EVaRT (Motion Analysis Corp., USA). The 3D marker coordinates were organized to represent 0–100% of the stance phase using 101 data points. The marker coordinates were then expressed as absolute distances from the pelvis centre, which was defined as the midpoint between right and left anterior superior iliac spines. The marker coordinates were also normalized to the static height of each subject to avoid differences in the movement patterns caused by different heights. The 3D marker coordinates of each individual trial were then vectorized to a 3636-dimensional vector (12 markers x 3 dimensions x 101 data points). Finally, an input data matrix was created for the SOM composed of the vectors of each trial of each subject (5 trials×88 subjects), yielding a matrix dimension of 440 x 3636 (Figure 3-1b).

3.2.3 Identification of Functional Groups

3.2.3.1 Group separation

Utilizing the SOM, a two-stage clustering was conducted to separate groups possessing different movement patterns (Vesanto and Alhoniemi, 2000). In the first stage, the SOM was trained with the input matrix using the following settings: 12 x 9 map units, linear initialization algorithm, batch training algorithm, and Gaussian neighbourhood function. The SOM was implemented through a toolbox (Kohonen, 2009) within a self-made MATLAB (The MathWorks Inc., USA) programme. In the second stage, *k*-means clustering was applied to the SOM outcome to isolate the different

groups. The *k*-means clustering algorithm requires a predefinition of the number of groups (*k*) to be separated. A frequent approach to determine the optimal group number for a given data set is to try different group numbers and choose the one with the best clustering result (Witten and Frank, 2005). To determine the best clustering result, the following procedure was used: the *k*-means clustering algorithm was conducted with different group numbers (k = 2–10). Then, the classification rate was determined between each of the groups for the different group numbers (e.g., for $k = 2$ one classification rate and for $k = 3$ three classification rates were computed). The largest *k* that achieved a minimal classification rate above 80% was defined as the optimal group number. This threshold was chosen to be consistent with results from previous studies that have obtained classification rates above 80% when using walking or running kinematics (Begg and Kamruzzaman, 2005; Wu et al., 2007; Nigg et al., 2012). Thus, performing this procedure allowed using an empirical and meaningful threshold for the optimal group number. The classification rates were determined by a leave-one-out cross-validation (LOOCV) that was applied using the SVM (Maurer et al., 2012). The classification rates in combination with a one-sided binomial test ($\alpha = 0.05$) were used to determine whether the separated groups had significantly different movement patterns. The SVM was utilized via a self-made programme using the MATLAB Bioinformatics Toolbox with default settings for C-parameter (i.e., 1) and 'autoscale' (i.e., true).

When executing the *k*-means clustering algorithm several times with the same input data, the clustering results can slightly differ. Thus, the *k*-means clustering algorithm was executed 10 times with each group number (*k*) and the corresponding classification rates were determined. Only the execution for each *k* with the highest minimal classification rate was considered for the above

described procedure to determine the optimal group number. Finally, the assessment rate was calculated for each group number (Schöllhorn et al., 2002).

3.2.3.2 Movement pattern differences and functional interpretation

The SVM was used with a linear kernel function to allow the determination of, and functionally interpretation of the group differences (Stirling et al., 2011). Using the linear kernel, a discriminant vector (i.e., the normal vector to the optimal separating hyperplane) was obtained. This discriminant vector indicated the spatiotemporal contribution of each marker to the separation of the two groups and could be used to study the movement pattern differences. To visualize the movement differences, the distinctive movement pattern of each group was obtained. To this purpose, the trials of each group were projected on the corresponding discriminant vector. The projection of each trial on the discriminant vector is referred to as score. The mean score of each group was used for the back-transformation in the original coordinate system (von Tscharner et al., 2013), which yielded the group-specific movement patterns normalized to the subject heights. The movement pattern of each group was multiplied by the mean subject height of both groups to express the movement patterns in real world units. The two movement patterns were then displayed using stick figures. The same SVM settings were used as outlined in the previous paragraph.

3.2.4 Differences in Age, Gender and Comfort Preferences

Each running trial of a group was associated with the age and gender of the corresponding individual. Using this input data, the classification rate (LOOCV) and the discriminant vector between each of the groups were determined with the SVM. The SVM settings were the same as described before. The significance of the classification rates was determined by means of a one-

sided binomial test ($\alpha = 0.05$). The characteristic (i.e., age or gender) that contributed the most to the group separation was revealed using the discriminant vector loadings. To determine differences in the comfort preferences, each running trial of each group was associated with the comfort points of the corresponding individual. Using this input data, the footwear condition (i.e., soft, medium or hard midsole) that contributed the most to the group separation, the classification rates, and the significance of the classification were determined by means of the aforementioned procedure. An overview table was created showing the group comparisons with significant differences in age/gender or comfort points, and the characteristic and footwear condition that contributed the most to the group differences.

3.3 Results

Eight was the largest number of groups with a minimal classification rate above the 80% threshold (Figure 3-2a). The assessment rate with eight separated groups was 97.1% (Figure 3-2b). The classification rates between the groups ranged from 81.3% to 100% (Table 3-1), which were all significant ($p < 0.001$).

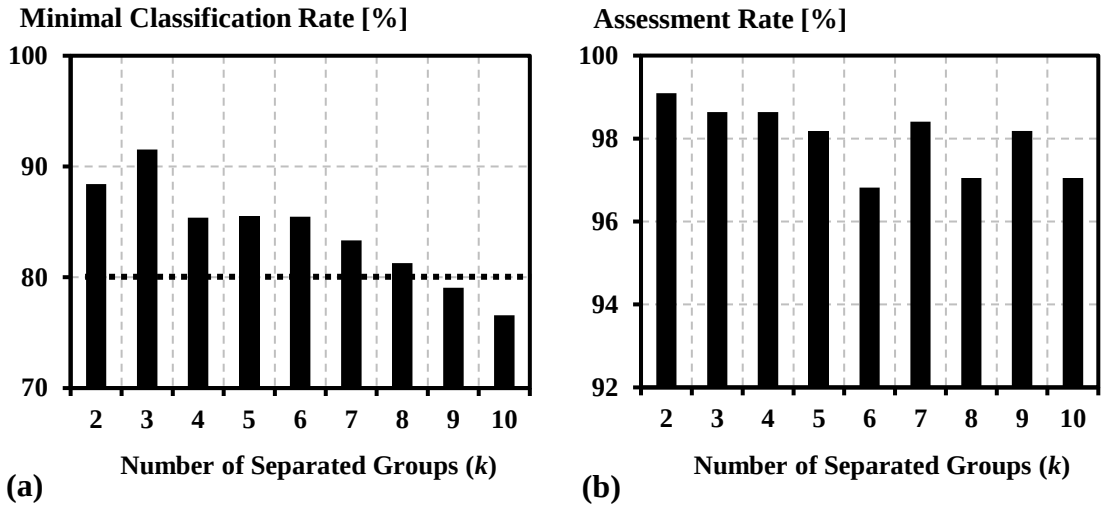


Figure 3-2: (a) Minimal classification rate for different numbers of separated groups. The black-dotted line indicates the defined threshold of 80%. (b) Assessment rate for different numbers of separated groups.

Table 3-1: Classification rates (CR) [%] for each group comparison. *N* represents the total number of trials in both groups. All classification rates were significant ($p < 0.001$) according to a one-sided binomial test ($\alpha = 0.05$).

Group Comparison	N	CR [%]	Group Comparison	N	CR [%]
1 vs. 2	70	100.0	**5 vs. 6**	110	98.5
1 vs. 3	105	100.0	**1 vs. 7**	86	100.0
2 vs. 3	125	96.4	**2 vs. 7**	106	85.8
1 vs. 4	74	81.3	**3 vs. 7**	141	89.2
2 vs. 4	94	93.0	**4 vs. 7**	110	86.7
3 vs. 4	129	92.1	**5 vs. 7**	100	100.0
1 vs. 5	64	100.0	**6 vs. 7**	132	97.7
2 vs. 5	84	100.0	**1 vs. 8**	95	96.0
3 vs. 5	119	97.0	**2 vs. 8**	115	100.0
4 vs. 5	88	100.0	**3 vs. 8**	150	93.9
1 vs. 6	96	100.0	**4 vs. 8**	119	92.8
2 vs. 6	116	99.2	**5 vs. 8**	109	82.7
3 vs. 6	151	81.3	**6 vs. 8**	141	99.4
4 vs. 6	120	98.1	**7 vs. 8**	131	91.3

The average age of the youngest group was 16.8 years (SD 0.8) and of the oldest group 54.9 years (SD 19.5; Figure 3-3). Group 4 was mainly composed of running trials of males (61.2%) and Group 5 was predominantly composed of female trials (66.7%). Groups 2, 3, and 6 rated the soft midsole as the most comfortable shoe condition (Figure 3-4). All other groups rated the medium midsole as the most comfortable shoe condition. For all groups, except Group 4, the least comfortable shoe condition was the hard midsole.

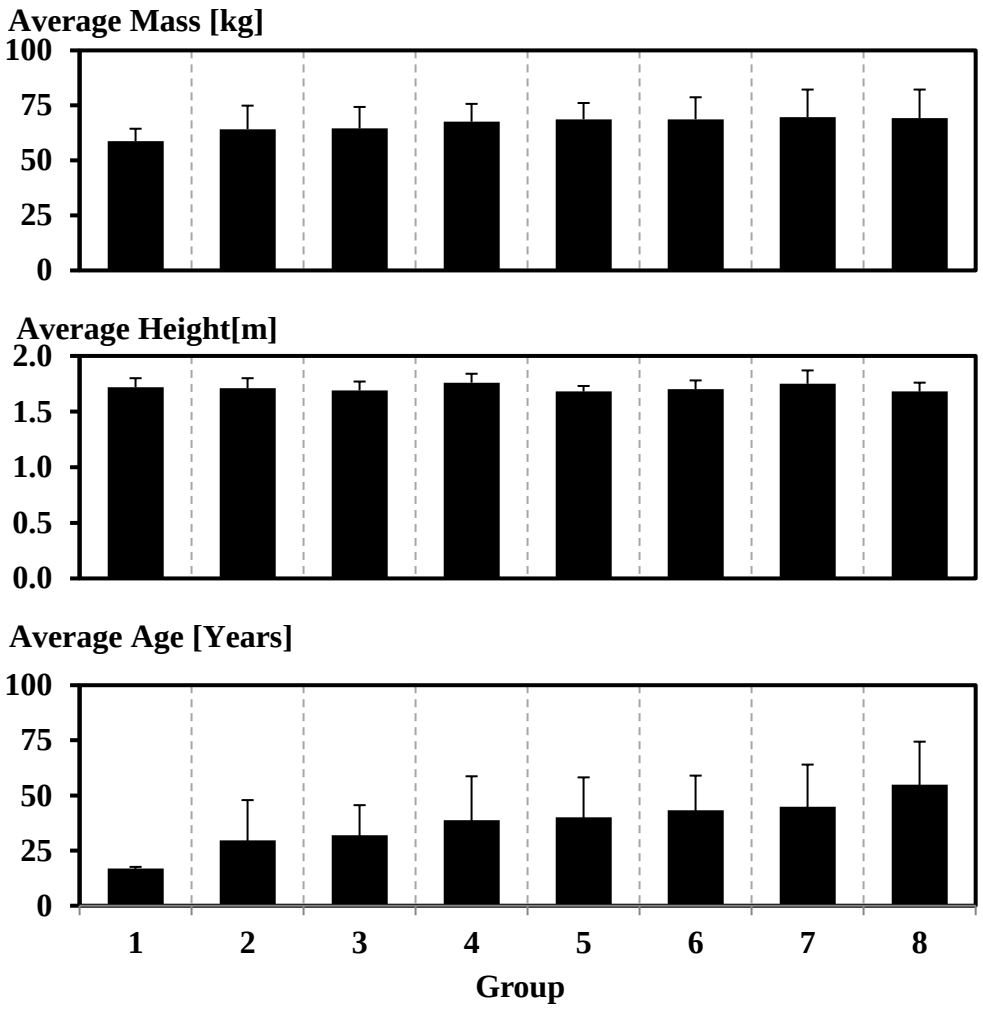


Figure 3-3: Profiles of the separated groups with different movement patterns: Average mass (mean ± SD), average height (mean ± SD), and average age (mean ± SD).

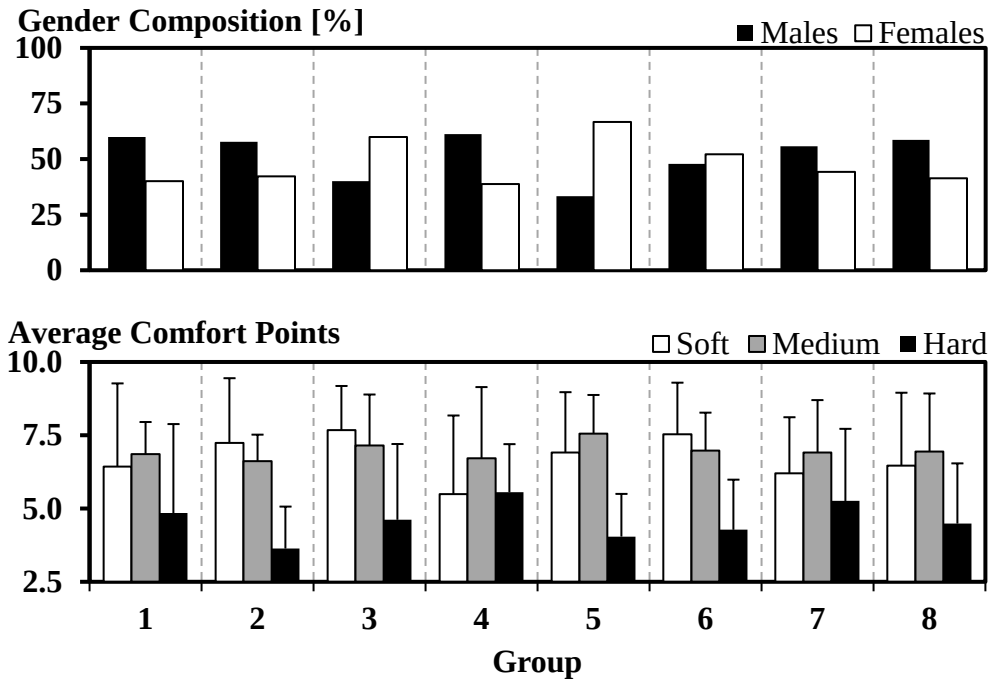
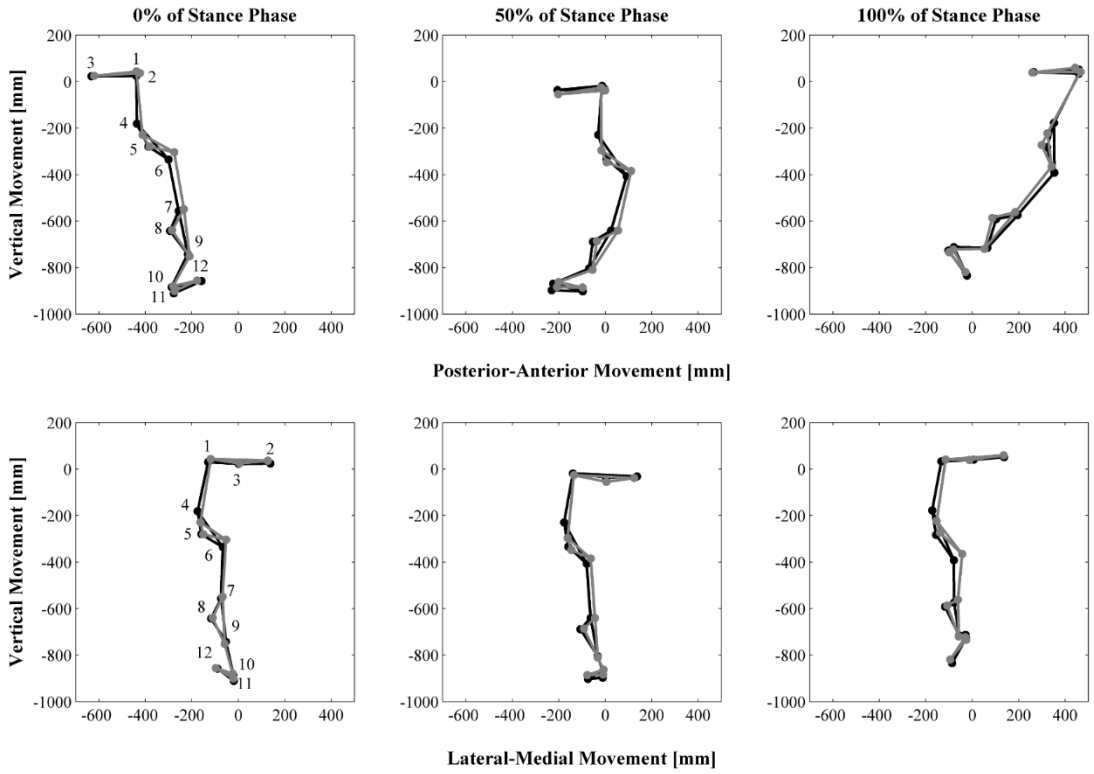
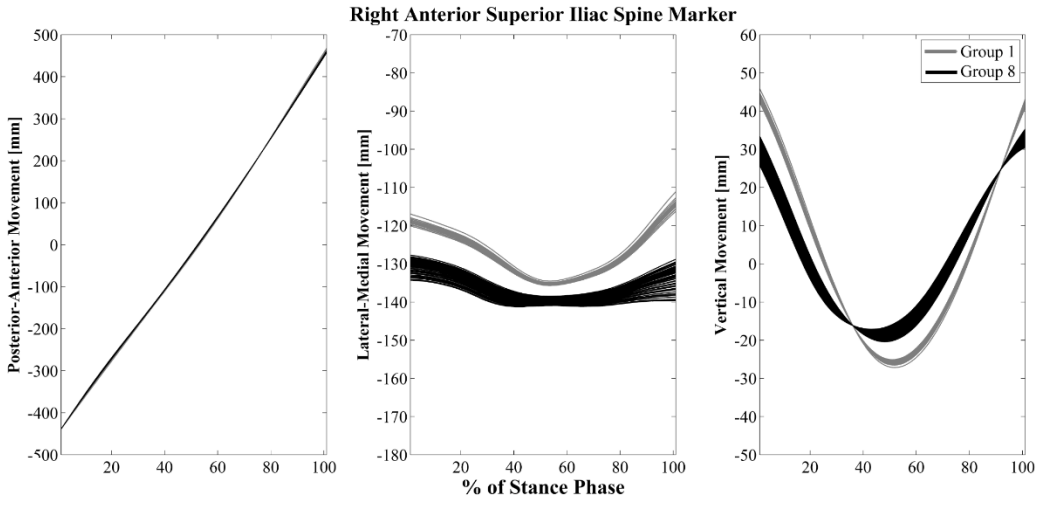


Figure 3-4: Profiles of the separated groups with different movement patterns: Gender composition and average comfort points (mean ± SD).

The movement pattern differences across the separated groups were determined and functionally interpreted. For example, Figure 3-5a displays the movement pattern differences between Groups 1 and 8 and Figure 3-6a between Groups 5 and 7. Group 8 showed a reduced vertical displacement of the pelvis (i.e., marker 1–3; individual trajectories of marker 1 are displayed in Figure 3-5b) throughout the stance phase compared to Group 1. The differences in the spatio-temporal marker locations also indicated a larger range of motion of hip and knee flexion/extension (i.e., marker 4–6) of Group 1. The main differences between Groups 5 and 7 occurred at the beginning of the stance phase (i.e., marker 4–9; individual trajectories of marker 4 are displayed in Figure 3-6b).



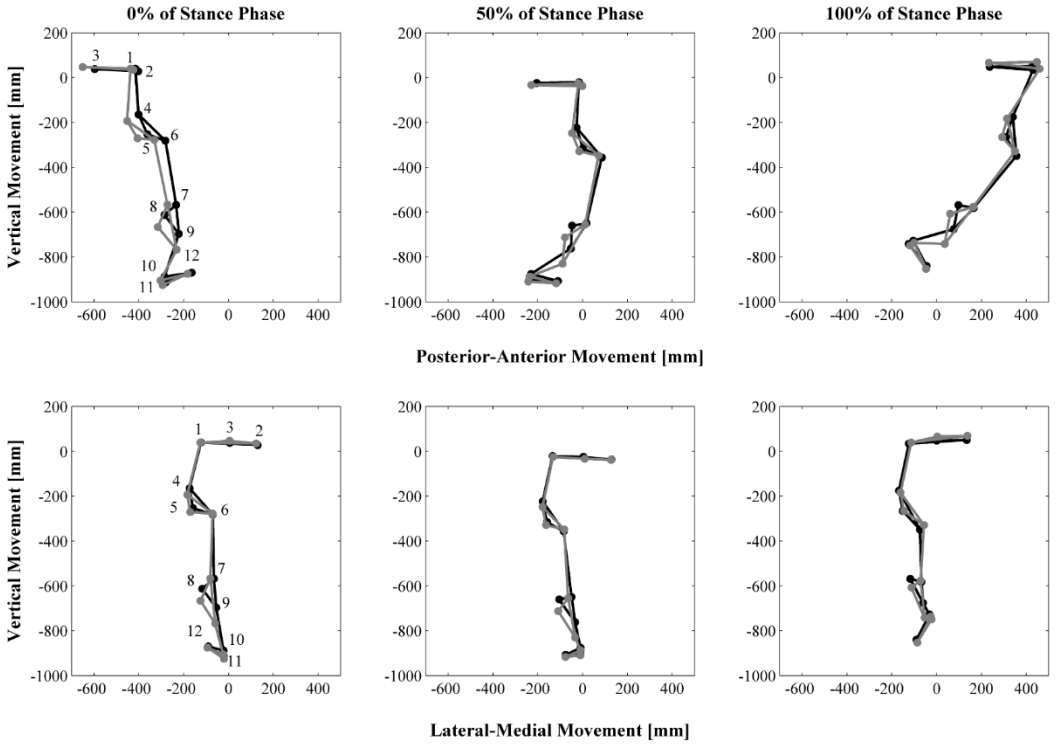
(a)



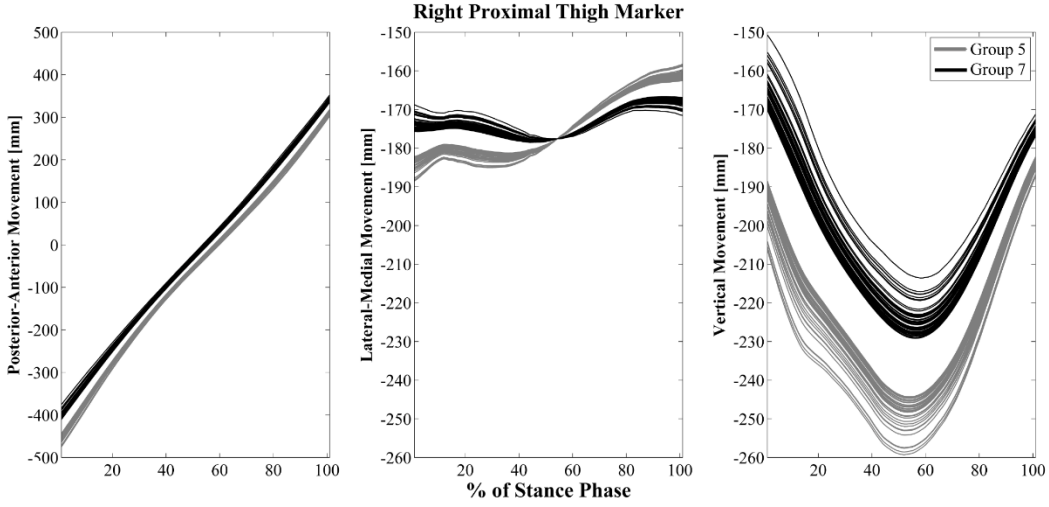
(b)

Figure 3-5: (a) Movement pattern differences between groups 1 (grey dots) and 8 (black dots), which differed in age; displayed by the differences in the individual marker (dots) trajectories at different instances of the stance phase: Marker 1–2 = right and left anterior superior iliac spine; 3 = lower back; 4–6 = right proximal, medial, and distal thigh; 7–9 = right proximal, medial, and

distal shank; 10–12 = high, low and lateral shoe (labels of black markers also valid for grey markers). The vertical and horizontal axes represent the vertical and posterior–anterior / lateral–medial running movement expressed as absolute distances from the pelvis centre. (b) Individual trajectories of the right anterior superior iliac spine marker of the members of groups 1 and 8.



(a)



(b)

Figure 3-6: (a) Movement pattern differences between groups 5 (grey dots) and 7 (black dots), which differed in the footwear-related comfort preferences; displayed by the differences in the individual marker (dots) trajectories at different instances of the stance phase: Marker 1–2 = right and left anterior superior iliac spine; 3 = lower back; 4–6 = right proximal, medial, and distal thigh;

7–9 = right proximal, medial, and distal shank; 10–12 = high, low and lateral shoe (labels of black markers also valid for grey markers). The vertical and horizontal axes represent the vertical and posterior–anterior / lateral–medial running movement expressed as absolute distances from the pelvis centre. (b) Individual trajectories of the right proximal thigh marker of the members of Groups 5 and 7.

Significant classification rates were found for 19 out of 28 possible group comparisons regarding age and gender (Table 3-2). Age was the characteristic with the highest contribution to group differences in most of the comparisons. A higher contribution of gender than of age was only observed in the comparison between male and female dominated groups (Groups 4 and 5). Four out of 28 group comparisons had significant classification rates regarding the comfort points with the highest contribution to the group differences associated with the hard midsole (Table 3-2).

Table 3-2: Overview of group comparisons where a significant difference was found in age / gender characteristics as well as comfort points. The x marks the characteristic (i.e., age or gender) and footwear condition (i.e., soft, medium, or hard midsole) that contributed the most to the group differences.

Group	Characteristics		Comfort Points		
Comparison	**Age**	**Gender**	**Soft**	**Medium**	**Hard**
1 vs. 3	X				
1 vs. 4	X				
2 vs. 4	X				
3 vs. 4			X		
1 vs. 5	X				
3 vs. 5	X				
4 vs. 5		X			X
1 vs. 6	X				
2 vs. 6	X				
3 vs. 6	X				
5 vs. 6				X	
1 vs. 7	X				
2 vs. 7	X				
3 vs. 7	X				
5 vs. 7					X
1 vs. 8	X				
2 vs. 8	X				
3 vs. 8	X				
4 vs. 8	X				
5 vs. 8	X				
6 vs. 8	X				
7 vs. 8	X				

3.4 Discussion

The study's main objective was to propose and apply a methodological approach based on SOMs (incl. *k*-means clustering) and SVMs to identify functional groups. To the authors' knowledge this is the first time that unsupervised and supervised pattern recognition techniques have been combined to automatically separate groups with different running kinematics and to determine the actual, significant differences in their movement patterns. The findings revealed that most of these groups differed in age or gender, which was an expected outcome. Some of the identified functional groups differed in their comfort ratings and, therefore, had group-specific footwear requirements. In fact, the proposed method was sensitive enough to find groups that had group-specific footwear requirements, but no age or gender differences. This finding suggests that age and gender are criteria that may separate groups with different movement patterns but are not necessarily the right criteria to identify functional groups with specific footwear requirements. This emphasizes the importance of the proposed methodological approach to address the specific needs of functional groups.

The study findings support the concept of functional groups and the feasibility of the applied approach to identify them. This work is only a first step towards identifying relevant functional groups in footwear research. The proposed methodological approach can be applied to identify groups that may later be investigated to better understand their distinct movement patterns and footwear requirements.

3.4.1 Identification of Functional Groups

3.4.1.1 Group separation

The combination of a SOM and a *k*-means clustering algorithm automatically separated eight groups with different running movements. Eight groups were chosen as this number revealed the best clustering results (Figure 3-2a). The assessment rate is a percentage value of the number of running trials of a single subject that are assigned to the same group. Since intra-subject variability can be expected to be lower than the inter-subject variability, the majority of a subject's trials should be assigned to the same group. This was found as the obtained assessment rate indicated that, in average, 4.9 (97.1% of 5 running trials) trials per subject were assigned to the same group. All classification rates (range: 81.3-100%) between the groups were significant (Table 3-1), indicating that the groups had statistically different movement patterns.

Limitations to the procedure used to determine the optimal group number are associated with intuitively and somehow arbitrarily selected parameters. Further, there was not a distinct separation in the minimal classification rates between $k = 8$ and $k > 8$ that would clearly support one group number over the other (Figure 3-2a). However, using eight groups for the subsequent analysis revealed that the majority but not all of the groups differed in age and/or gender and, therefore, had age and gender specific movement patterns. This might be an indicator for the validity of the chosen group number as previous studies emphasized the dominance of age and gender on human locomotion (Ferber et al., 2003; Fukuchi and Duarte, 2008). Still, some groups (e.g., Groups 5 and 7) differed neither in age nor gender (Table 3-2). As stated in the introduction, age and gender are frequently used characteristics to pre-group individuals to study group-specific

movement patterns. This study showed that when using predefined groups based on these characteristics some groups with distinctive movement patterns might not be detected.

Footwear midsole characteristics have been shown to primarily influence kinematics (Hardin et al., 2004) and muscle activity (Wakeling et al., 2002), and seem to effect kinetics less during locomotion (Nigg et al., 1987; Cole et al., 1995). In this study, the identification of the functional groups was based on running trials performed with a moderate midsole condition (Asker C-52). It was assumed that this common footwear characteristic might be the best representation of the participants' shod running movement pattern. Additionally, one might postulate that biological characteristics (e.g., gender) have a stronger influence on movement patterns than different footwear conditions (Ferber et al., 2003; Nigg, 2010; Maurer et al., 2012). Since it was speculated that the distinctive movement patterns of the functional groups are due to their characteristics, different footwear conditions may not significantly influence the presented grouping. Furthermore, although shod, heel-toe running might be the preferred running condition for the majority of people; future studies defining functional groups should also consider barefoot movement patterns without the influence of footwear interventions as well as different footfall patterns.

3.4.1.2 Movement pattern differences and functional interpretation

Movement pattern differences between the youngest (Group 1: 16.8 years) and the oldest group (Group 8: 54.9 years; Figure 3-5) such as a reduced vertical displacement of the pelvis, which indicates a reduced vertical displacement of the Centre of Mass, have also been reported previously (Karamanidis and Arampatzis, 2005). The proposed analysis approach allowed determining movement pattern differences between groups that would not have been identified using the

common grouping criteria age or gender. For example, movement pattern differences between groups (5 and 7), which showed significant differences in their comfort points, could be identified (Figure 3-6). Differences in leg alignment or arch height may be potential factors causing group-specific movement patterns and comfort preferences (Heiderscheit et al., 2000; Miller et al., 2000; Mündermann et al., 2001; Williams III et al., 2001). It is speculated that the identification and the subsequent functional interpretation of the movement pattern differences are necessary to match footwear features to the distinctive movement patterns of functional groups. Future studies could use the proposed approach to identify aetiologic factors associated with particular movement patterns. Group-specific footwear features that account for these factors (e.g., reducing extensive foot pronation) might help to reduce the incidence of running injuries. The proposed pattern recognition approach is not limited to kinematics or to functional groups with specific footwear requirements. In the future other bio-signals (e.g., muscle activity data) to identify functional groups with other group-specific requirements (e.g., group-specific apparel) could be used.

3.4.2 Differences in Age, Gender and Comfort Preferences

The majority of the groups differed in age and only two groups (4 and 5) differed in gender (Table 3-2). This indicates that age is a dominant factor causing distinctive movement patterns (Begg and Kamruzzaman, 2005; Fukuchi and Duarte, 2008). Gender-based movement pattern differences have also been documented previously (Ferber et al., 2003). Overall, this study supported the observation that age and gender are important characteristics associated with group-specific movement patterns. Therefore, studies should further investigate whether these age/gender groups have specific footwear needs. However, some of the groups did not differ either in age or gender. Besides age and gender, other characteristics that may cause distinct movement patterns are

anthropometric features (Nawoczenski et al., 1998; Heiderscheit et al., 2000) or previous injuries (Donoghue et al., 2008). Midsole hardness is only one of several footwear features influencing comfort perceptions (Mills et al., 2010). Nevertheless, using different modifications of this footwear feature revealed that some of the groups had different comfort preferences (Table 3-2). Importantly, several groups with differences in their comfort preferences showed no differences in age or gender. Therefore, an essential practical interpretation of this finding is that when identifying functional groups simply using age or gender, footwear requirements of certain groups might not be detected.

3.5 Conclusion

A functional group is a collection of individuals who react in a similar way to a certain intervention/product. In this study, a pattern recognition approach was used that allowed automatically identifying these groups using their distinctive movement patterns. This is important because when identifying functional groups simply using common grouping criteria like age or gender, certain groups with group-specific movement patterns and product requirements might not be detected.

Chapter Four: Intra-Rater Reliability of Footwear-Related Comfort Assessments

4.1 Introduction

Comfort is one of the most important aspects of footwear (Nigg, 2010). Comfort is a key consideration for many consumers when purchasing new footwear and an essential feature in the development of new footwear products. Enhanced footwear comfort has also been suggested to reduce the likelihood of exercise-related injuries (Mündermann et al., 2001; Kinchington et al., 2011), and may be associated with improved neuromuscular control of balance (Burke, 2012). Improvements in running economy have also been reported with enhanced running footwear comfort (Luo et al., 2009). In addition to these beneficial effects associated with sports and recreational footwear, comfort is also an important factor for footwear serving as a medical device. For example, it has been reported that comfort perception influences the prescription and fitting process of foot orthoses (Doxey, 1985; Mündermann et al., 2001; Mills et al., 2011). It has also been suggested that patients do not adhere to uncomfortable foot orthoses (Mündermann et al., 2003; Mills et al., 2012), which would ultimately limit the desired treatment effect.

Given the importance of footwear comfort in sports-related, recreational and clinical settings, understanding its aetiology and effects is essential for professionals working with footwear or orthotics. For example, understanding footwear comfort is important for shoe and orthoses makers to adequately adjust product designs, for clinicians to determine the effects on treatment, and for researchers to quantify the influence on the musculoskeletal system. Participant-specific characteristics such as anthropometry, skeletal alignment, foot sensitivity, and plantar pressure patterns have been associated with perceived footwear comfort (Chen et al., 1994; Miller et al.,

2000; Mündermann et al., 2001). Footwear design features such as fit, torsional stiffness, cushioning, support, and stability have also been suggested to influence comfort (Nigg et al., 1999; Miller et al., 2000; Reinschmidt and Nigg, 2000; Mündermann et al., 2001; Mills et al., 2010). Contradictory findings have been reported regarding comfort and its impact on the musculoskeletal system. A few studies found that changes in footwear comfort were associated with changes in lower extremity kinematics, kinetics, and muscle activity during locomotion (Chen et al., 1994; Mündermann et al., 2003, 2004). Others did not find an influence of footwear comfort on the kinetics during locomotion (Wegener et al., 2008; Dinato et al., 2015).

Mills et al. (2010) has stated that footwear-related comfort may be described as an ever-changing perception of an individual, which is the result of mechanical, neurophysiological, and psychological factors (Chen et al., 1995; Nigg et al., 1999; Miller et al., 2000; Mündermann et al., 2001). Given its multifactorial nature, a common challenge in studies investigating the aetiology and effects of footwear comfort is that it is difficult to quantify comfort. Various measurement techniques have been used to quantify footwear comfort such as Visual Analog Scales (VASs), Likert Scales, ranking scales, and perception scales (Llana et al., 2002; Hagen et al., 2010; Mills et al., 2010; Lane et al., 2014). Furthermore, specific studies have been conducted to identify appropriate measurement techniques for quantifying footwear comfort. Mündermann et al. (2002) reported that VASs seem to provide a reliable measure for the assessment of footwear comfort. Mills et al. (2010) tested the reliability of VASs, Likert Scales, and ranking scales for quantifying footwear comfort and supported the finding that the VAS provides a reliable measure to quantify footwear-related comfort.

Although it seems that previous research has identified appropriate and reliable measures (e.g., VAS) to assess footwear comfort, little is known about the reliability of a given individual to assess footwear comfort on different occasions (i.e., between-day intra-rater reliability). Findings from Mündermann et al. (2002), based on a limited sample size, suggest that there are differences in the reliability among individuals. Although intuition would suggest that the majority of individuals have high intra-rater reliability when the mechanical, neurophysiological, and psychological factors that may influence footwear comfort remain constant, this has not been tested specifically. In addition, it is unknown whether the level of complexity of the measure used to quantify comfort has an effect on intra-rater reliability. Individuals with poor between-day intra-rater reliability would provide inconsistent comfort assessments under consistent testing conditions and, therefore, might not be able to truly assess footwear comfort. Comfort assessments with poor reliability might be potential confounding factors in studies investigating the aetiology and effects of footwear comfort and may also provide footwear manufacturers with inaccurate evaluations of future products. In orthotic therapy, poor intra-rater reliability might also be taken into consideration when determining the role of comfort with respect to orthoses prescription/fitting and treatment success. It is, therefore, crucial to investigate intra-rater reliability of footwear comfort assessments to identify and better understand individuals with low reliability and to develop strategies to account for this poor reliability.

The objectives of this study were (1) to determine the between-day intra-rater reliability of footwear-related comfort assessments across several individuals and (2) to investigate whether intra-rater reliability is influenced by the complexity of the measure used to assess comfort. The hypotheses to be tested were:

(1) The majority of healthy individuals can reliably assess footwear comfort between days by means of Visual Analog Scales.

(2) Reducing the complexity of the comfort measure, by changing from Visual Analog Scales to Yes-No questions, is associated with more reliable footwear comfort assessments.

4.2 Methods

4.2.1 Study Participants

Ninety physically active male adults participated in this study (age: 29.3 ± 7.5 years; height: 1.79 ± 0.05 m; mass: 77.9 ± 8.5 kg; mean ± SD). Study participants were recruited from a greater metropolitan area based on the following inclusion criteria: 18-50 years, males, general good health, free of any serious lower-extremity pain in the last six months, and no respiratory conditions (e.g., breathing difficulties), forms of arthritis, neuromuscular and neurological disorders, or heart problems. The study protocol was approved by the Conjoint Health Research Ethics Board (REB13-0331). All participants provided written informed consent.

4.2.2 Experimental Protocol

The different footwear conditions used in this study were based on a neutral running shoe (model Boston, adidas AG, GER) with one control insole and six test insoles. The control insole was the default insole of the running shoe. The six test insoles varied systematically in material and shape characteristics (Table 4-1). The tested insole conditions possessed characteristics similar to frequently used and commercially available foot insoles/orthoses. The neutral running shoe was available in different shoe sizes (US 9, 10, and 10.5) and the test insoles were fitted to each shoe size. Participants were blinded to the test insoles. This was achieved by ensuring that the participants were not able to see which test insole was put into the neutral running shoe before a measurement trial. Participants were informed when they were using the control insole.

Table 4-1: Characteristics of the six test insoles used in this study.

Name	Thickness Forefoot	Thickness Rearfoot	Hardness	Elasticity	Shape Arch	Shape Heel
Flat Thin	2 mm	2 mm	Hard Asker C 60-70	Visco-elastic	Flat	Flat
Flat Soft	5 mm	10 mm	Soft Asker C 25-35	Elastic	Flat	Flat
Flat Hard	5 mm	10 mm	Hard Asker C 60-70	Elastic	Flat	Flat
Flat Gel	5 mm	10 mm	Soft Asker C 25-35	Visco-elastic	Flat	Flat
Shaped Soft	5 mm	10 mm	Soft Asker C 25-35	Elastic	High	Spherical
Shaped Hard	5 mm	10 mm	Hard Asker C 60-70	Elastic	High	Spherical

For each participant three comfort assessment sessions were conducted. There was a break of a minimum of six days between each testing session to avoid potential participant recall of comfort assessments from previous sessions, which would artificially increase the reliability. The maximum length of the break was aimed to be seven days, but was allowed to vary. The time of the day when the testing session took place (i.e., morning, afternoon, etc.) was kept consistent for each study participant across the three testing sessions to reduce possible confounding factors with the comfort perception. At each testing session a modified version of the experimental protocol from Mündermann et al. (2002) was used. Before each testing session the study participants received written information about the testing procedure and about the questions to be answered.

Afterwards, participants performed a warm-up run on a 200 m indoor track in their own running shoes for a self-selected duration. Following the warm-up procedure, the actual testing session began, where participants performed one approximately 200 m run on the track in each footwear condition. During each run, participants were asked to maintain a comfortable, self-selected running pace. The participants were administered the footwear conditions in the following order: C-TI1-C-TI2-CTI3-C-TI4-C-TI5-C-TI6, where C is the control insole and TI# represents one of the six test insoles in randomized order (insoles were randomized between participants and sessions). To randomize the test insoles, an identification number (1-6) was assigned to each test insole and the Microsoft Excel (Microsoft Corp., Redmond, WA, USA) function 'RANDBETWEEN' was utilized. Following the first run in the control insole and after each run in the test insoles, participants were asked to assess footwear comfort. Comfort ratings from previous testing sessions were not visible for the study participants. Participants, however, were allowed to see the rating of an already tested footwear condition at the very same testing session.

Footwear comfort was assessed using two measures: VASs and Yes-No questions. The VAS had a length of 150 mm with anchor points 'Not comfortable at all' (= 0 mm) and 'Most comfortable insole imaginable' (= 150 mm). Using VASs was justified by the fact that this measurement technique has been frequently utilized to assess footwear comfort (Burke, 2012; Lane et al., 2014; Dinato et al., 2015), and that VASs have been shown to provide an appropriate measure to quantify footwear comfort (Mündermann et al., 2002; Mills et al., 2010). The VAS is a continuous scale representing a rather complex measure to quantify footwear-related comfort. In contrast, Yes-No questions that provide binary information may represent a more simplistic measure to quantify footwear comfort. Consequently, the following Yes-No questions were asked: (1) 'Was the insole

comfortable? Yes/No' and (2) 'Was the insole uncomfortable? Yes/No.' VASs and Yes-No questions were administered using a paper-pencil based questionnaire.

4.2.3 Data Analysis

The first testing session's purpose was to familiarize the participants with the research study and experiment protocol. This was done to avoid any potential bias in the comfort assessments related to the novelty of the study participations. As such, only the data from the last two testing sessions were considered for the analysis. To answer the main research question focusing on the intra-rater reliability of footwear-related comfort assessments, the VAS scores of each of the test footwear conditions (i.e., the six test insoles) were used for the reliability calculations. The control condition served as a neutral basis between the test conditions and was not considered for analysis. To investigate the influence of the complexity of the comfort measure on intra-rater reliability, the reliability was calculated based on the Yes-No questions and compared with the reliability obtained based on the VASs.

4.2.4 Intra-Rater Reliability Assessment

With respect to the VAS, intra-rater reliability was determined by calculating the intra-class correlation coefficient (ICC or $ICC_{(2,1)}$, respectively) and the minimal detectable change (MDC or MDC_{95}, respectively) for each study participant (McGraw and Wong, 1996; Tilson et al., 2010). Unlike the MDC, the ICC is a coefficient with no unit that can be compared across different reliability studies. Thus, thresholds have been established that allow judging the quality of the reliability (Atkinson and Nevill, 1998; Bruton et al., 2000). Using these established thresholds, the participants were classified in groups of individuals with a high or acceptable reliability (ICC ≥

0.7), and individuals who were not able to reliably assess footwear-related comfort (ICC < 0.7). The intra-rater reliability based on the Yes-No questions was assessed using Cronbach's alpha (Cortina, 1993). A Cronbach's alpha value ≥ 0.7 was considered as an acceptable reliability (Cortina, 1993).

4.3 Results

The absolute difference between the VAS scores of the two testing days for each study participant and test footwear condition (i.e., the six test insoles) is displayed in Figure 4-1.

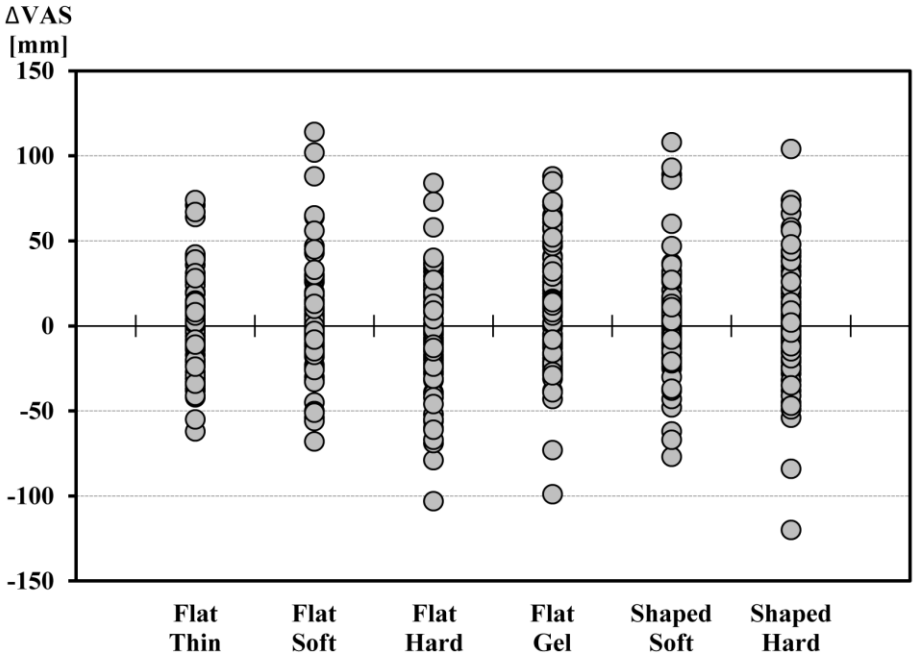


Figure 4-1: Absolute difference between the Visual Analog Scale (VAS) scores of the two analysed testing days for each study participant (dots) and test footwear condition: ΔVAS = VAS Score $_{Day1}$ - VAS Score $_{Day2}$.

For 31.1% (28 out of 90) of the study participants an ICC ≥ 0.7 was achieved using VASs to assess footwear comfort (Figure 4-2a). A negative ICC value was obtained for 13.3% (12 out of 90) of the participants. The MDC ranged from 10.4 to 143.4 mm (mean MDC: 54.8 mm); in general, lower MDC values were achieved by participants with ICC values larger than 0.7 (Figure 4-2b).

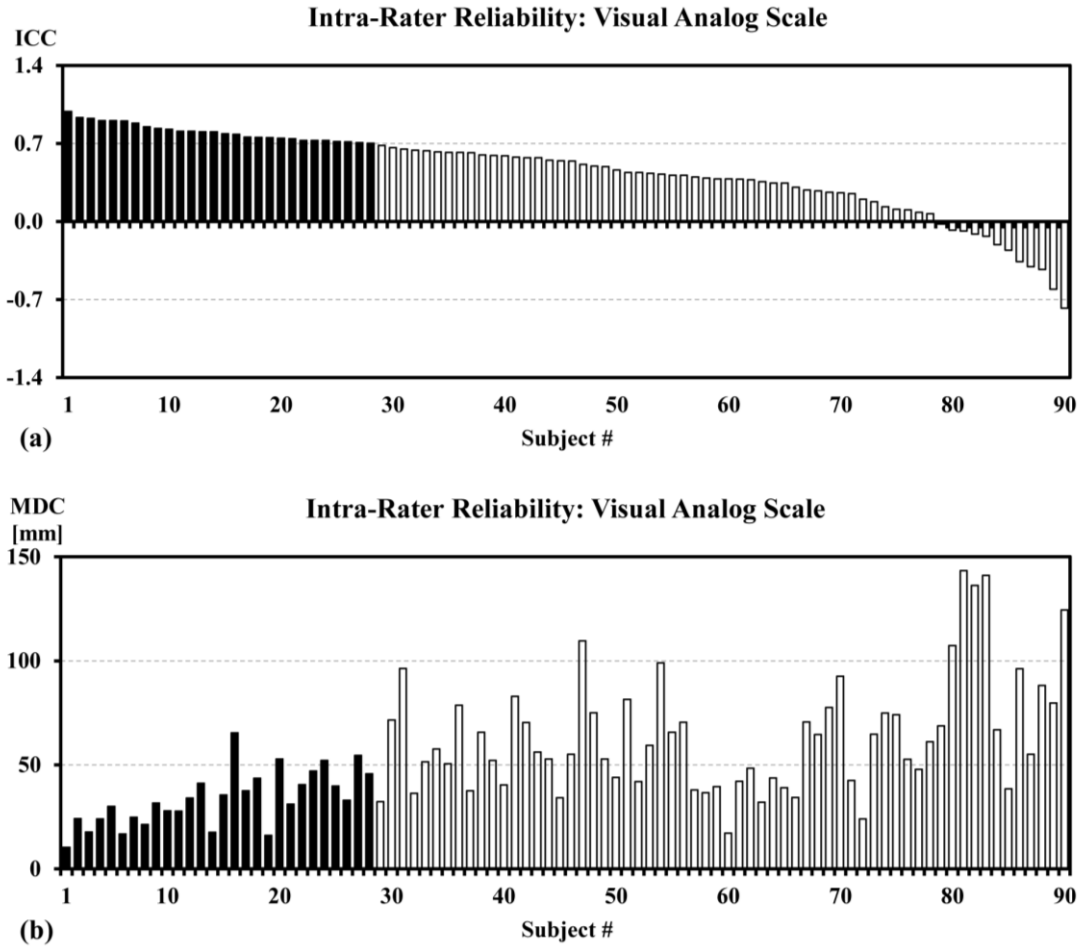


Figure 4-2: (a) Intra-class correlation coefficients (ICCs) and (b) minimal detectable change (MDC) for footwear-related comfort assessments based on Visual Analog Scales. In both graphs, black bars indicate individuals that had an ICC ≥ 0.7 and, therefore, were considered to be reliable in their assessments. Participants are ranked by decreasing ICC value.

The VAS scores of the individual with the highest ICC (0.99) as well as lowest MDC (10.4 mm), the individual with the lowest ICC (-0.78), the individual with the highest MDC (143.4 mm), and an individual with a low ICC (0.38) and MDC (17.2 mm), are displayed in Figure 4-3.

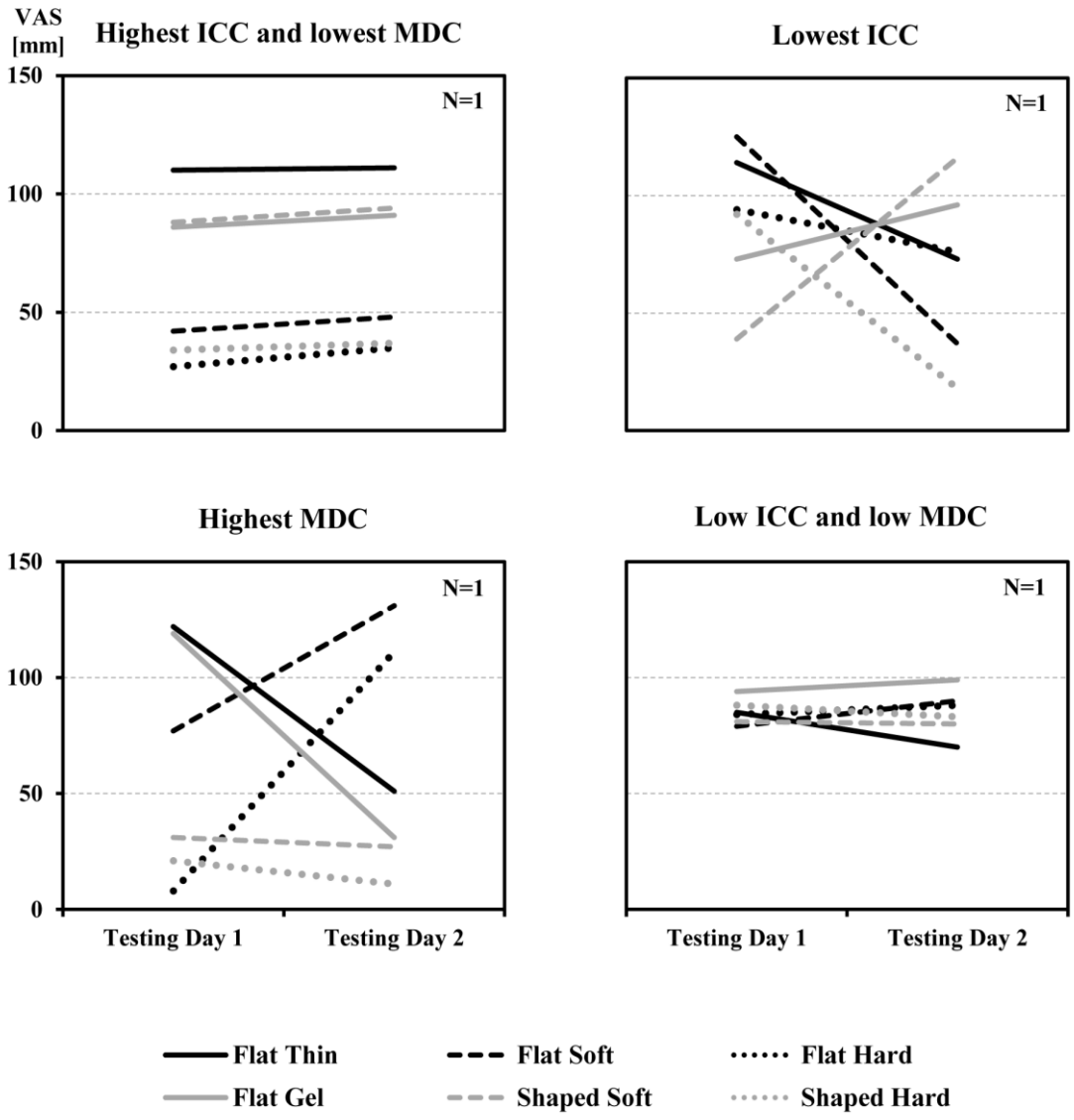


Figure 4-3: The Visual Analog Scale (VAS) scores of the individual with the highest intra-class correlation coefficient (ICC) and the lowest minimal detectable change (MDC) (top-left), the lowest ICC (top-right), the highest MDC (bottom-left), and an individual with a low ICC and low MDC (bottom-right) at the two analysed testing days.

When determining the intra-rater reliability based on Yes-No questions, 46.7% (42 out of 90) of the individuals had a Cronbach's alpha value that was ≥ 0.7 (Figure 4-4). For 28.6% (8 out of 28) of the participants who had reliable assessment (i.e., ICC ≥ 0.7) based on the VAS, an unreliable assessment with the Yes-No questions was obtained.

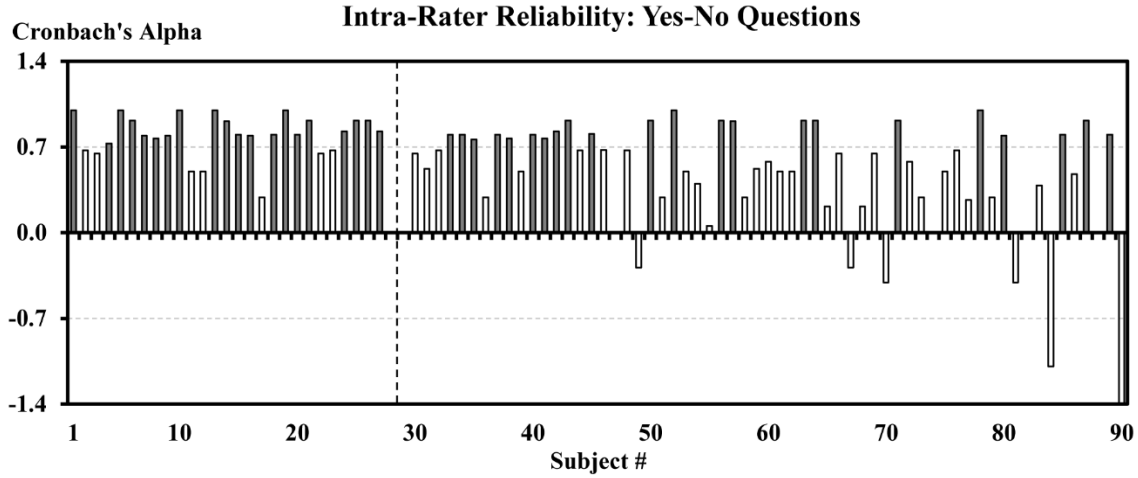


Figure 4-4: Cronbach's alpha for footwear-related comfort assessments based on Yes-No questions. Filled bars indicate individuals who had a Cronbach's alpha ≥ 0.7 and, therefore, were considered to be reliable in their assessments. Individuals are ranked by decreasing ICC values and the vertical dotted line separates reliable and non-reliable assessments based on the ICCs. Note that the Cronbach's alpha value of participant #90, which is -2.96, is not completely displayed in the graph.

4.4 Discussion

The objective of this study was to quantify the intra-rater reliability of footwear-related comfort assessments. To the best knowledge of the authors, this is the first study that specifically focused on the reliability of comfort assessments in individuals between different testing days.

Footwear comfort perceptions differ across different individuals (Chen et al., 1994; Mündermann et al., 2001). It was hypothesized that the majority of individuals can assess comfort in a reliable fashion. However, a reliable assessment of footwear-related comfort (i.e., ICC $\geq$ 0.7) was only obtained for a minority of individuals (i.e., 31.1%) with respect to insoles with common design and material characteristics (Figure 4-2a and Table 4-1). Therefore, the first hypothesis of the study was rejected. There are several reasons that might explain low intra-rater reliability. Comfort perception might be associated with mechanical, neurophysiological, and psychological factors (Chen et al., 1995; Nigg et al., 1999; Miller et al., 2000; Mündermann et al., 2001; Mills et al., 2010). Although the study was carefully designed to keep the mechanical (e.g., same footwear conditions, same fit) and neurophysiological states (e.g., same motor task) constant across testing sessions, it is difficult to control for certain factors influencing the psychological state. Despite the fact that a framework was provided that would allow for a controlled, similar psychological condition between the testing sessions (e.g., same instructor, same oral, and written instructions), the psychological state of the participants could have varied across the testing sessions. As a simple example, the psychological state could have varied depending on whether the participant had a 'good' or 'bad' day at work. Since the psychological condition at the beginning of the testing session was not quantified, it remains unknown whether this had an influence on intra-rater reliability. Hence, future studies should investigate if and how much psychological variables (e.g.,

mood) can influence footwear comfort perceptions. However, if such a perturbation would have existed in this study, one could expect that this would have affected the reliability of only few of the tested individuals. Differences in the intra-rater reliability among individuals might also be explained by different lengths of the break between the testing days. During longer breaks, for example, participant-specific characteristics associated with footwear comfort (e.g., plantar pressure patterns) could have changed (e.g., from a new training program), causing different footwear comfort perceptions at the two testing days. However, there was no significant difference in the mean ICC value between the individuals with a break of ≤ 7 days (57.8% of individuals; ICC: 0.48 ± 0.34, mean ± SD) and those with a break of > 7 days (42.2% of individuals; ICC: 0.41 ± 0.41). In addition, the ICC values of the individuals with the three longest breaks were -0.21 (63 days), 0.91 (44 days), and 0.43 (42 days). Age also had no influence on intra-rater reliability since no significant difference was found in the mean ICC value between the 20 youngest (age: 20.5 ± 1.6 years; ICC: 0.52 ± 0.36; mean ± SD) and 20 oldest study participants (age: 40.1 ± 5.0 years; ICC: 0.53 ± 0.38). Another factor contributing to the observed differences in intra-rater reliability and to the high number of people with low reliability may be participant-specific foot sensitivity thresholds (Mündermann et al., 2002). Individuals with a low reliability may have low receptor sensitivity on the plantar surface of the feet. Thus, the differences between the footwear conditions may not have provided sufficient afferent sensory information for these individuals in order to clearly distinguish them at the testing sessions. However, future studies are required to clarify the observed differences in the reliability of footwear comfort assessments among individuals.

Mündermann et al. (2002) and Mills et al. (2010) previously studied the reliability of measurement techniques for quantifying footwear comfort. These authors found that performing comfort

assessments on multiple consecutive days improves the reliability of a comfort *measurement technique.* This study, however, had the purpose to determine the reliability of a given *individual's* comfort assessments on non-consecutive days. This study design was chosen because it was assumed that it represents a comfort assessment situation similar to those that often occur in scientific research projects, in footwear development, or when purchasing new footwear. Therefore, it is speculated that quantifying intra-rater reliability using isolated comfort assessments based on different, non-consecutive days represents a practical and relevant testing scenario.

A negative ICC value was obtained for 13.3% of the participants in this study. Negative ICCs have been controversially discussed in the literature and the informative value of negative ICC values has been debated (Giraudeau, 1996; Varnell et al., 2004; Hallgren, 2012). While these results should be interpreted with caution, the general statement can be made that participants with negative ICC values have an insufficient intra-rater reliability (Hallgren, 2012).

In this study, a commonly applied criterion (ICC < 0.7) was used to identify individuals with a non-reliable footwear comfort assessment. However, in certain practical settings when trying to improve footwear comfort such individuals cannot simply be neglected. Thus, it might be important to understand how much a footwear condition has to change the comfort perception/assessment to represent a 'meaningful' and reliable change. In this regard, the MDC was calculated (Figure 4-2b), which indicates the smallest change on the VAS that would be considered to be meaningful and real (Tilson et al., 2010). Different types of minimal meaningful differences for footwear comfort perception have been identified in the past. Mills et al. (2010) determined a clinically important change in comfort of about 10 mm based on a 100 mm VAS.

Using previous comfort studies (Mündermann et al., 2001, 2002, 2003), Burke (2012) estimated a minimal meaningful difference of 20-25 mm, mainly based on 150 mm VASs. In this study, only a few individuals (12.2%) had an MDC below 25 mm. However, the important result was that the MDC was participant-dependent. The practical implication of this finding is that one has to establish a MDC for each individual in order to be able to evaluate whether a certain footwear or foot orthoses does enhance footwear comfort. The MDC is directly calculated from the ICC (Tilson et al., 2010), and there is an inherent negative correlation between these two variables. However, some of the participants showed a low ICC in conjunction with a low MDC (Figure 4-3). Such a relationship was given when an individual tended to use only a small range of the available VAS. The largest MDC values were obtained for individuals with a negative ICC value. Again, because the calculation of the MDC did include the negative ICC values, these MDC results should be interpreted with caution.

The second hypothesis of the study stated that using a measure with a lower complexity than the VAS would allow for improved intra-rater reliability. This hypothesis was supported as the number of individuals who had a reliable footwear comfort assessment was increased by reducing the complexity of the measure from the VAS to simple Yes-No questions (Figure 4-4). In fact, 46.7% of the participants had a reliable comfort assessment using simple Yes-No questions, compared to 31.1% reliable comfort assessments with the VASs. This is in agreement with previous research suggesting that the complexity of the measure can influence the reliability of comfort assessments (Mills et al., 2010). However, simple measurement techniques such as ‘Yes-No’ questions might limit the information that can be obtained. Compared to VASs, ‘Yes-No’ questions do not allow to evaluate how much footwear conditions differ in comfort levels. Nevertheless, if one wants to

determine whether a given footwear condition is simply comfortable or not, measures with lower complexity seem to be advantageous.

A potential limitation of the study is the generalizability of the presented results. A homogenous cohort consisting of able-bodied male individuals was used. Statements about the intra-rater reliability with respect to footwear-related comfort assessments of other populations (e.g., females) have to be made with caution and be confirmed from future studies. Nevertheless, there is no reason to speculate that the intra-rater reliability may be higher for any other population. In fact, intra-rater reliability may be lower for individuals with somatic sensory system deficiencies. As mentioned above, the experimental design of this study was developed to perform comfort assessments similar to those that often occur in practical and relevant situations (e.g., footwear-related studies). In this study, the test insoles had characteristics similar to the features of commercially available foot orthoses with rather moderate shape and material characteristics. Despite these rather moderate characteristics, a broad range of VAS ratings was obtained. For 52.2% of the participants, the difference between the lowest and highest VAS rating was at least 75 mm at one of the two analyzed testing sessions. This seems to indicate that the different test insoles caused considerably different footwear conditions. However, future studies might investigate whether footwear conditions with more extreme characteristics may improve intra-rater reliability. In addition, future research is also required to study whether increasing the amount of time each participant tests the different footwear conditions can increase intra-rater reliability.

The main finding of this study was that the majority of individuals tested were not able to reliably assess footwear comfort. Therefore, caution is advised when assessing comfort for shoe and/or

orthotic selection or for research purposes. In fact, when using footwear comfort in orthotic therapy, footwear development, or scientific research projects, one should account for this low reliability of comfort assessments. Strategies to account for a poor reliability may be (1) simplifying the measure used to assess footwear comfort, (2) only selecting individuals who were pre-tested for reliable assessments, and/or (3) establishing mean comfort ratings for an individual across multiple testing sessions. It is important to mention, that depending on the objective of the footwear comfort assessment one has to carefully evaluate which strategy can be used. In orthotic therapy, for example, it is most likely not possible to only select individuals with reliable assessments. In this instance, using simplified comfort measures might be a more appropriate strategy. Additionally, future research aiming to better understand the reason for low intra-rater reliability might also help to develop additional strategies such as increasing the amount of time footwear conditions have to be worn.

4.5 Conclusion

The majority of individuals tested in this study were not able to reliably assess footwear-related comfort, with only a third of them providing reliable comfort assessments across testing days. The reason for this inability is unclear. A higher number of reliable comfort assessments might be achieved by simplifying the measure used to quantify footwear comfort.

Chapter Five: Functional Grouping in Running using Footwear Comfort

5.1 Introduction

One key objective of footwear biomechanics is to support the development of products that promote health and/or athletic performance. People, however, can have individual solutions (e.g., movement patterns, joint loadings) when performing a motor task in the same footwear product (e.g., Bates et al., 1983; Hreljac, 1998; Nester et al., 2003; Erhart et al., 2008). A footwear intervention can therefore be beneficial for one person, but ineffective or even disadvantageous for another individual. Functional grouping is an attempt to address the observation that people respond differently to the same footwear (Nigg, 2010). A functional group is a collection of individuals with similar and group-specific functional solutions when performing a motor task. In footwear biomechanics, a functional group can therefore be defined as a collection of individuals with similar, specific functional solutions while wearing a given sport shoe. Matching footwear features to these functional groups may support the development of footwear that promotes health and/or performance (Nigg, 2010).

Matching footwear to a functional group, however, is a difficult and poorly understood process. First, one must identify the different functional groups. Second, one must tailor footwear constructions to the functional solutions of the identified groups to improve their athletic performance and/or to reduce their injury risk. This study focuses on the first aspect, and therefore aims to provide a better understanding of how functional groups can be identified.

Groups are often identified using sex or age as grouping criteria (Ferber et al., 2003; Fukuchi et al., 2011; Nigg et al., 2012). The limitation of this method is that even within cohorts that appear homogenous (i.e., similar age, same sex), functional groups might exist (Hoerzer et al., 2015b). Another approach to identify functional groups is to cluster individuals with similar functional solutions (Hoerzer et al., 2015b). However, this approach requires that the functional solutions of all individuals have previously been measured. One approach without the above-mentioned limitations is based on footwear comfort, and has not yet been investigated. Comfortable footwear has been associated with increased performance and reduced injury risk (Mündermann et al., 2001; Luo et al., 2009). It is therefore speculated that a shoe is comfortable because it supports a person's functional solutions. Consequently, if one member of a functional group perceives a shoe as comfortable, all other members having similar functional solutions will do so as well. If this speculation is correct, footwear comfort, in combination with biomechanical assessments, may be used to identify functional groups using the following steps:

1. Select a group of individuals who rate the same footwear as comfortable
2. Exclude all individuals from this group who exhibit functional solutions that are different from the majority of the group

Therefore, the study objective was to test the proposed methodological steps and identify one functional group of runners. If the proposed procedure can identify a functional group, then the following hypothesis needs to be confirmed: Most of the individuals who select the same footwear to be comfortable have similar and group-specific functional biomechanical solutions when performing a motor task and, therefore, form one functional group.

5.2 Methods

In the first part of this study, a *comfort assessment* was conducted to identify two groups who either selected a given footwear as comfortable (Group C) or uncomfortable (Group U; Figure 5-1).

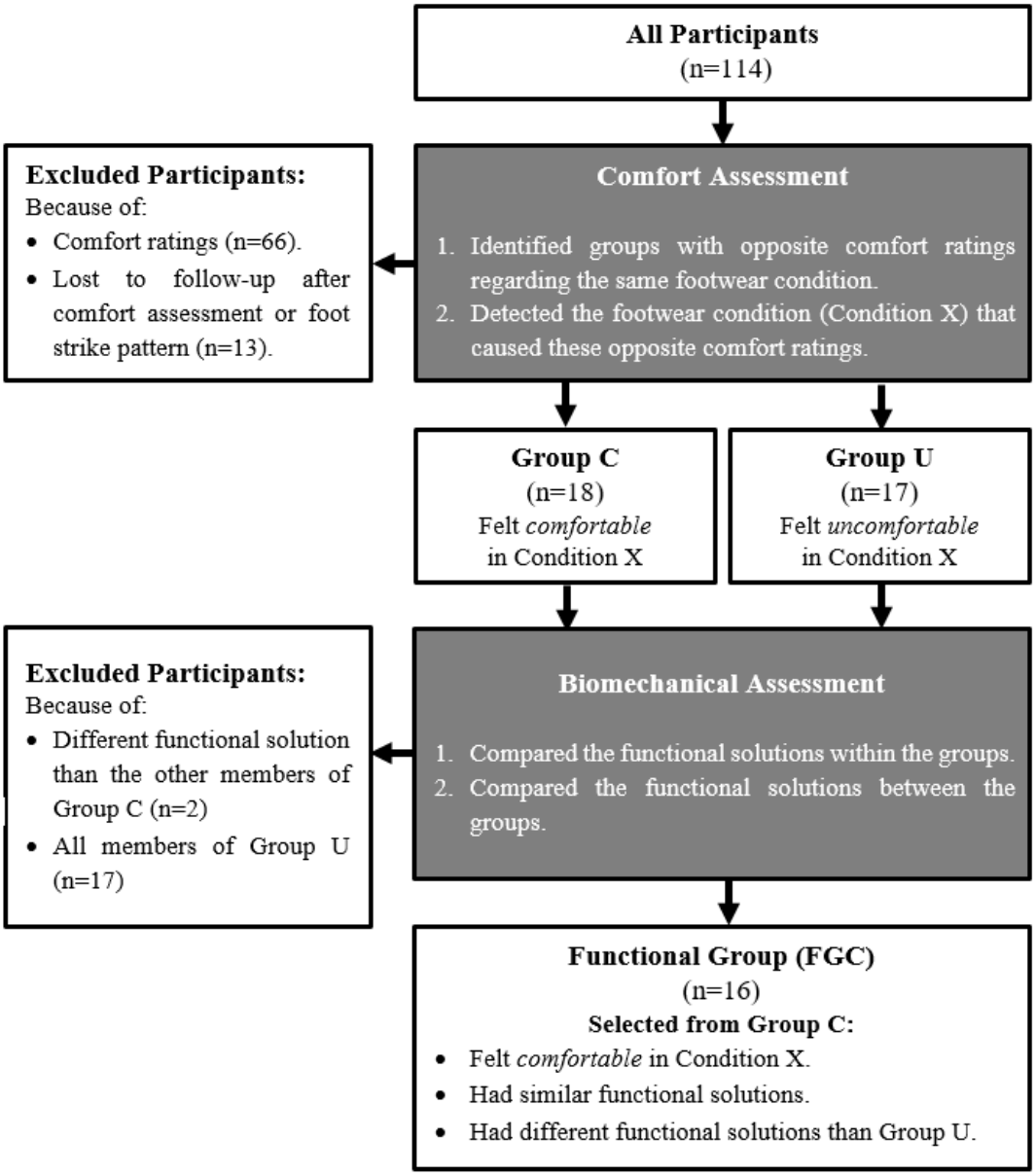


Figure 5-1: Flow chart demonstrating the study design.

Second, a *biomechanical assessment* was performed to define one functional group (FGC) from the members of Group C to test the outlined hypothesis. The functional group to be identified had two key characteristics: (a) same comfort assessments, and (b) similar and group-specific kinematics and muscle activity data. Kinematics and muscle activity data were chosen to describe the functional solutions. Although this selection was to a certain extent arbitrary, it was assumed that these movement and motor control related data sufficiently describe a group's functional solutions.

5.2.1 Study Participants

In total, 114 recreational athletes (mean ± standard deviation: age: 28.6 ± 7.1 years, height: 1.79 ± 0.05 m, mass: 76.8 ± 8.3 kg) participated in the comfort assessment. Participants had to meet the following inclusion criteria: males, 18-50 years, in general good health, free of any lower-extremity pain and injuries at the time of testing. The study was approved by the appropriate research ethics board, and all participants provided written informed consent.

5.2.2 Comfort Assessment

5.2.2.1 Experimental Protocol

Each participant completed one familiarization and two testing sessions on different days. Subjects ran at a comfortable, self-selected pace for about 200 m on an indoor track in each footwear condition. The footwear conditions consisted of a control insole (standard insole of the running shoe) and six test insoles (Table 5-1), all worn in the same neutral running shoe (Boston, adidas AG, GER). The participants were blinded to the differences between the test insoles. Insoles were given to the participants in the following order (Mündermann et al., 2002): C-In1-C-In2-C-In3-C-

In4-C-In5-C-In6, (C = control insole; In# = one of the six test insoles in randomized order). Participants rated footwear comfort of the test insoles directly after running with them using a Visual Analog Scale (VAS) with anchors “Not comfortable at all” (= 0 mm) and “Most comfortable insole imaginable” (= 150 mm).

Table 5-1: Material and shape characteristics of the test insoles.

Name	Thickness Forefoot	Thickness Rearfoot	Elasticity	Shape Arch	Shape Heel	Hardness
Flat - Thin	2 mm	2 mm	Visco-Elastic	Flat	Flat	Hard: Asker C 60-70
Flat - Gel	5 mm	10 mm	Visco-Elastic	Flat	Flat	Soft: Asker C 25-35
Flat - Soft	5 mm	10 mm	Elastic	Flat	Flat	Soft: Asker C 25-35
Flat - Hard	5 mm	10 mm	Elastic	Flat	Flat	Hard: Asker C 60-70
Shaped - Soft	5 mm	10 mm	Elastic	High	Spherical	Soft: Asker C 25-35
Shaped - Hard	5 mm	10 mm	Elastic	High	Spherical	Hard: Asker C 60-70

5.2.2.2 Grouping

For each test insole, the minimal detectable change (MDC) was calculated based on the comfort ratings of all participants for this condition on both testing session. Comfort assessments of an individual for a given footwear can differ between testing sessions (Hoerzer et al., 2016). Taking

into account this variance, the MDC describes how much the comfort ratings have to differ on the VAS to represent a 'real' difference (Tilson et al., 2010). Next, the mean comfort rating of each insole for each individual across the two testing sessions was calculated to obtain one representative rating. The MDC was then used to form two groups for each of the six test insoles (Figure 5-2).

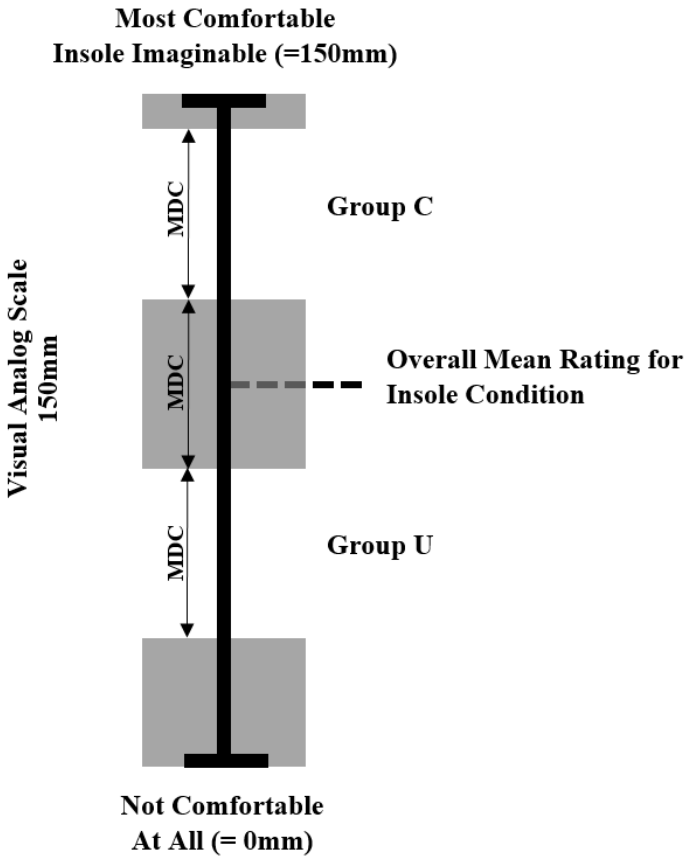


Figure 5-2: Schematic demonstrating the procedure used to identify two groups with conflicting comfort ratings. Groups (white areas) on the Visual Analog Scale (thick black lines) were defined using the minimal detectable change (MDC). Group C was composed of people who had ratings ranging from an insole condition's overall mean rating *plus* 0.5*MDC to 1.5*MDC. Group U had comfort ratings between the overall mean *minus* 0.5*MDC to 1.5*MDC.

Using these MDC-based groups ensured that there was a 'real' difference in the comfort ratings between the groups, and no difference within one group. The grouping procedure revealed two groups for each footwear condition: Group C felt comfortable and Group U felt uncomfortable with the same footwear condition. The insole (condition X) that caused the largest group sizes (Group C: n = 26; Group U: n = 22) was chosen for the biomechanical assessment.

5.2.3 Biomechanical Assessment

For the biomechanical assessment, 18 participants of Group C, and 17 subjects of Group U were recruited (Figure 5-1). The remaining subjects could not be recruited due to loss to follow-up after the comfort assessment, or due to their foot strike pattern (i.e., forefoot runners were excluded due to their distinct running style).

5.2.3.1 Experimental Protocol

Following a short warm-up run with the control insole, subjects performed 10 successful heel-toe over-ground running trials with condition X and with another insole condition, which was neglected for the subsequent analysis. A running trial was successful if the participant's foot landed within the edges of the force platform (Kistler Instrumente AG, Switzerland; sampling frequency: 2400 Hz) while running at a speed of 3.5 ± 0.5 ms^{-1}. During each running trial, kinematic, kinetic, and muscle activity data of the right lower extremity were collected. Kinetic data (i.e., vertical ground reaction force) were only used to identify heel-strike and toe-off (force threshold: 20 N).

Kinematics were collected using a marker-based 3D motion capture system (Motion Analysis Corp., USA; sampling frequency: 240 Hz) with 11 retro-reflective markers (Figure 5-3a), which were used to define four body segments (Figure 5-3b).

Pelvis
Defined by the right and left anterior and posterior superior iliac spine markers
Thigh
Defined by the right greater trochanter and lateral epicondyle of the right femur markers
Shank
Defined by the lateral epicondyle of the right femur and the right medial and lateral malleoli markers
Shoe
Defined by markers at the right heel located proximally and distally, and at the head of the right 5th metatarsal bone

(b)

Figure 5-3: (a) Front view of the marker locations. In total, 11 markers were used in this study: 1 - right anterior superior iliac spine, 2 - left anterior superior iliac spine, 3 - right posterior superior iliac spine (not visible in the picture), 4- left posterior superior iliac spine (not visible in the picture), 5 - right greater trochanter, 6 - lateral epicondyle of the right femur, 7 - right medial malleolus, 8 - right lateral malleolus, 9 - right proximal heel (not visible in the picture), 10 - right distal heel (not visible in the picture), 11 - head of the right 5th metatarsal bone. (b) Description of how the 11 markers were used to define the four segments: pelvis, thigh, shank, and shoe.

Electromyography (EMG) was used to measure the activity of five major muscles of the right lower extremity: the vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), gastrocnemius medialis (GM), and tibialis anterior (TA). EMG signals were recorded using bipolar Ag/AgCl surface electrodes (Norotrode dual electrodes, Myotronics Inc., USA). The inter-electrode spacing was 22 mm, with 10 mm diameter of each electrode. A ground electrode was placed on the tibial tuberosity. Electrodes were positioned on the muscle bellies according to SENIAM recommendations (Hermens et al., 1999), after carefully preparing the skin (i.e., shaving the hair, abrading with sand paper, and cleaning with isopropyl wipes). Electrodes and amplifiers were secured to the skin with medical tape to minimize movement artifacts. EMG signals from the electrodes were pre-amplified and band-pass filtered (10-500 Hz) before being recorded (sampling frequency: 2400 Hz).

5.2.3.2 Kinematic Data Pre-Processing

The 3D marker trajectories were reconstructed using Cortex 3 (Motion Analysis Corp., USA). The marker waveforms were then expressed as absolute distance from the pelvis center (i.e., mean of the four pelvis markers) to avoid kinematic differences due to different locations of the subjects in the lab coordinate system. The marker waveforms were normalized to the body height of each participant. Kinematic waveforms were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 12 Hz (Lamb et al., 2011). Waveforms were analyzed for two time windows pre-heel-strike and post-heel-strike. The length of each time window was defined by the duration of the stance phase. The pre-heel-strike window included the time from approximately mid-swing to initial heel contact (-100 to 0%, where 0% is heel-strike). The other window consisted of the entire stance phase of running (0 to 100 %). For two subjects (one in each group),

kinematic data were not available for both time windows; therefore these subjects were neglected for the kinematic analysis.

5.2.3.3 EMG Data Pre-Processing

A wavelet analysis was used to resolve the raw EMG signals in time-frequency space (von Tscharner, 2000) using 13 non-linear wavelets (Stirling et al., 2011). The center frequencies of the wavelets ranged from 6.9 to 542 Hz. Raw EMG signals and time-frequency patterns of the wavelet transform were visually inspected for measurement noise. The sum over all frequency bands (wavelets) at each time point yielded the EMG total intensity waveform. This waveform represents a close approximation to the EMG root-mean-square (von Tscharner, 2000). To obtain the EMG total intensity waveforms, the data of frequency bands 3 to 11 for each time point were summed. Four frequency bands were excluded: 1, 2, 12, and 13, as they often contain movement artifacts and measurement noise (von Tscharner, 2000; Nigg and Gérin-Lajoie, 2011). For each muscle, EMG total intensity waveforms were amplitude-normalized to the maximum moving average of EMG total intensity waveforms, obtained from isometric maximum voluntary contractions (MVCs). MVCs were obtained on a Biodex System 3 Pro dynamometer (Biodex Medical Systems, USA) using a standard protocol similar to the one described by Albertus-Kajee et al. (2011). In fact, for each muscle two MVCs were performed in a sitting position for about three seconds with the joint angles: 60° knee flexion for RF, VL, and BF; 30° knee flexion and 0° ankle flexion for TA and GM. A Grubbs test was performed ($\alpha = 0.01$) based on the peak of each EMG total intensity waveform to exclude potential outliers (Grubbs, 1969). EMG total intensity waveforms were time-normalized using the same two time windows as used for the kinematic

analysis. EMG data were synchronized to the kinematic data via heel-strike using simultaneously recorded acceleration data at the right heel.

5.2.3.4 Data Analysis and Statistics

The data analysis included time-continuous information. While standard statistical tests require a pre-selection of time-discrete variables (e.g., peak of a waveform), using time-continuous data provides the advantage of analyzing the kinematic and EMG waveforms as a whole (Maurer et al., 2012). To analyze the time-continuous data, nine input matrices were defined (four for the kinematic data, five for the EMG data). For the kinematic data, an input matrix for each of the four body segments was created, composed of rows containing the subjects and columns containing the averaged marker waveforms (based on the collected trials) for each subject. For the EMG data, an input matrix for each of the five muscles was created, including subjects and their corresponding averaged EMG total intensity waveforms. Rows of the input matrices represented vectors in a multi-dimensional vector space that formed the basis for the subsequent analyses.

To identify the functional group, FGC, a silhouette analysis determined which individuals shared similar data. The silhouette analysis provides a value (ranging from -1 to +1) that demonstrates how well an object belongs to its group (Rousseeuw, 1987). To obtain this value, the distance (Squared Euclidean distance) between an object and its group members is compared to the distance between the same object and members of other groups. A positive value shows that the object is closer to its own group members than to members of other groups. Although the silhouette analysis is mainly used to study appropriate cluster numbers in data sets (Rousseeuw, 1987), it was assumed that it also provides information about which individuals share similar data. A positive silhouette

value suggests that an individual has data like the other group members. A negative silhouette value shows that an individual belongs to a different group, which suggests that the individual has data different compared to its group members. Furthermore, a group with mainly positive values reflects a group with internal data similarity, whereas a group with mainly negative values has data dissimilarity. For each subject, a silhouette value was obtained for each of the four kinematic and five EMG matrices. Using these single values, two average silhouette values were obtained for each subject: one for the kinematic data, and the other for the EMG data. To identify the FGC, all individuals were excluded from Group C who had functional solutions that were different than the other group members. Specifically, all individuals with a negative average silhouette value for either the kinematic or EMG data were excluded.

To investigate whether the functional solutions of FGC were group-specific, the kinematic and EMG data were compared between the FGC and Group U using a Support Vector Machine (Vapnik, 1995) with a leave-one-out cross-validation (Eskofier et al., 2013). Utilizing this pattern recognition based approach, classification rates were computed for each of the kinematic and EMG matrices demonstrating how well the group members could be classified. A one-sided binomial test ($\alpha = 0.05$) was used to test whether the rates were high enough to indicate significant group differences. In this study, the SVM was only used as a tool to determine if the two groups had significant group differences. Therefore, the SVM was not utilized with the purpose to determine whether or not an individual belonged to its group.

The demographic information and comfort ratings between FGC and Group U were compared using independent samples t-tests ($\alpha = 0.05$).

5.3 Results

The Flat-Thin insole (i.e., condition X) was selected to define the groups. Group C felt comfortable (rating: 120.0 ± 10.3 mm; mean ± SD) in this footwear condition, while Group U perceived it as not comfortable (rating: 42.1 ± 11.1 mm; Table 5-2).

Table 5-2: Demographic information and comfort ratings (based on a 150 mm Visual Analog Scale) of Group C, the functional group, and Group U (mean ± SD). The functional group was comprised of the remaining members of Group C once all individuals who exhibited functional solutions different to the rest of the group were removed. The last row presents the p-values when comparing the functional group to Group U.

		Demographics			**Comfort Rating**
	N	**Age [yrs]**	**Height [m]**	**Mass [kg]**	**Flat-Thin [mm]**
Group C	18	29.9 8.0	1.78 0.05	77.3 7.4	120.0 10.3
Functional Group	16	30.5 8.3	1.78 0.06	75.3 4.3	121.2 10.3
Group U	17	30.8 6.1	1.76 0.05	78.1 9.3	42.1 11.1
p-value		**0.90**	**0.16**	**0.27**	**<0.001**

Group C was defined as the individuals who perceived the Flat-Thin insole to be comfortable. In this group, 16 out of 17 individuals had an average silhouette value of > 0 based on the kinematic data (Figure 5-4a). Conversely, Group U, who consisted of individuals that perceived the Flat-Thin insole as not comfortable, contained only 1 out of 16 individuals with a positive silhouette value. For the EMG data, 17 out of 18 individuals in Group C showed a silhouette value of > 0, but only 2 out of 17 in Group U (Figure 5-4b). The two individuals of Group C with negative silhouette values for either the kinematic or the EMG data were excluded. Figure 5-5 visualizes the differences in the data between the individuals with negative silhouette values and those with positive silhouette values. For one subject in Group C, no kinematic data were available and therefore no silhouette value for the kinematics was obtained. Since this subject's EMG-based silhouette value was positive, it was not excluded from FGC. Thus, 16 out of 18 individuals (88.9%) of Group C formed the functional group, FGC (Table 5-2).

No significant differences were found between FGC and Group U in age, height, and body mass (Table 5-2). Conversely, significant differences in the thigh, shank, and foot kinematics and in the EMG total intensity waveforms of the RF and TA could be detected between FGC and Group U while running with the Flat-Thin insole (Table 5-3).

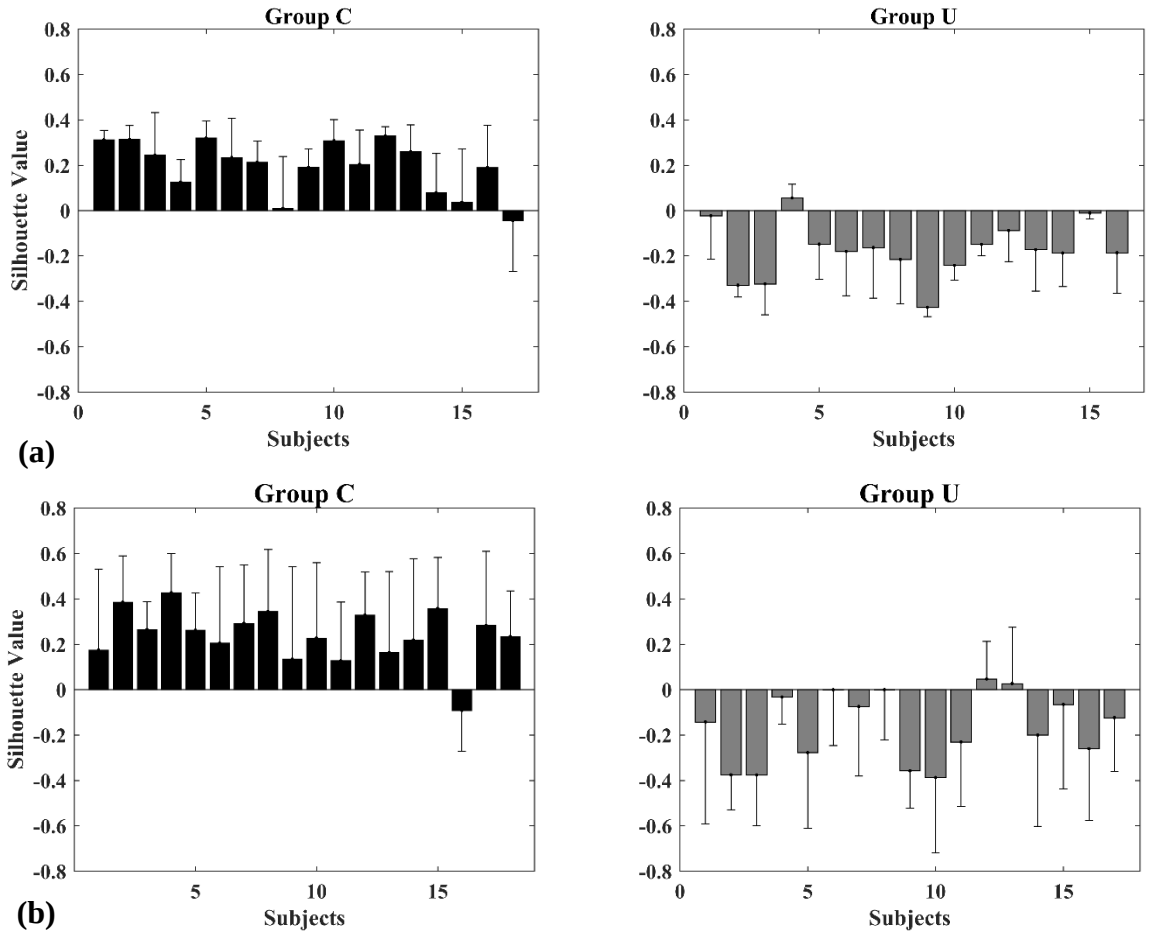


Figure 5-4: Silhouette values (mean + or - SD) for (a) kinematic and (b) EMG data for the Group C (left) and Group U (right).

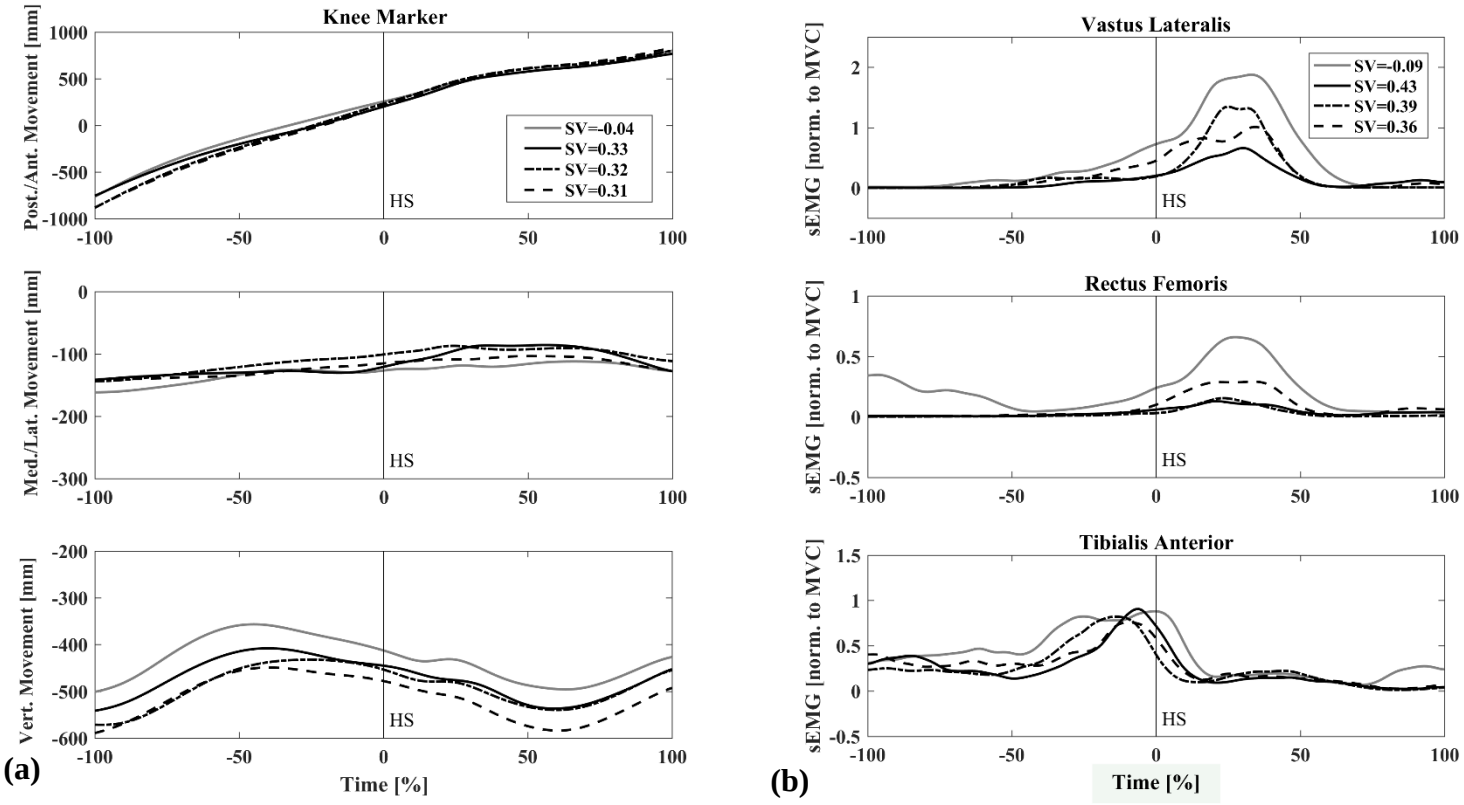


Figure 5-5: (a) Average knee marker waveforms for the subject with a negative silhouette value (grey line) and the three subjects with the highest silhouette values (black lines) for the kinematic data in Group C. (b) Average EMG total intensity waveforms of selected muscles for the subject with a negative silhouette value (grey line) and the three subjects with the highest silhouette values (black lines) for the EMG data in Group C. (SV = Silhouette Value; HS = Heel Strike).

Table 5-3: Classification rates and p-values for the comparisons between the functional group (FGC) and the uncomfortable (Group U). Classification rates demonstrate how well the data can be classified into one or the other group. Classification rates that were high enough to represent significant differences between groups are in bold.

Kinematics (Segments)		**Muscle Activity**	
Pelvis	51.6 % (p=0.5)	Vastus Lateralis	65.6 % (p=0.055)
Thigh	**74.2 % (p=0.005)**	Rectus Femoris	**73.3 % (p=0.008)**
Shank	**67.7 % (p=0.035)**	Biceps Femoris	56.3% (p=0.298)
Foot	**71.0 % (p=0.015)**	Tibialis Anterior	**69.7 % (p=0.018)**
		Gastrocnemius Medialis	51.6% (p=0.500)

5.4 Discussion

This study proposed a methodological approach to identify functional groups based on (a) footwear comfort, and (b) kinematics and EMG. To verify this approach, the hypothesis was tested that most individuals who select a footwear condition as comfortable have similar and group-specific functional solutions when performing a motor task. Supporting this hypothesis, most individuals (88.9%) who selected the tested footwear as comfortable had similar kinematics and muscle activity data during running. In addition, significant differences in the biomechanical solutions were revealed between the identified functional group, FGC, and a group of people who rated FGC's comfortable footwear as not comfortable. This finding supported the outlined hypothesis by indicating that FGC had group-specific functional solutions. As per the definition, a functional group could therefore be identified in this study. Consequently, the proposed methodology has the capability to functionally group runners. It is important to note that the functional group was identified from a homogenous (age and sex) athlete cohort. It is therefore likely that the proposed approach can also reveal other unknown functional groups from such a cohort. Such groups may provide the basis for new innovative, customized footwear segments in the sporting goods industry.

Footwear comfort perceptions differ among individuals (Mündermann et al., 2001). In this study, opposing comfort ratings for the same footwear were used to reveal different groups of runners. The footwear condition with the highest number of conflicting ratings was a combination of a neutral running shoe with a minimalist, hard insole (i.e., "Flat-Thin", Table 5-1). Footwear hardness is one of the key features influencing comfort perception (Mündermann et al., 2001). Group U may have perceived this footwear condition as too hard and, therefore rated it as not

comfortable. This assumption is supported by the observation that the most comfortable condition of the members of Group U were predominantly soft insoles (i.e., 12x Shaped Soft, 3x Flat Soft, 2x Flat Gel). In contrast, the Flat-Thin insole may have provided the right level of hardness for FGC, and therefore was perceived as comfortable. Given the performance and health benefits associated with comfortable footwear (Mündermann et al., 2001; Luo et al., 2009; Kinchington et al., 2011), it may be speculated that the Flat-Thin insole promotes health and performance of the identified functional group, FGC. Therefore, future studies should investigate beyond merely identifying functional groups using comfort, but also investigate whether the ideal footwear for the athletes can also be selected using comfort.

All individuals in Group C selected the Flat-Thin insole as comfortable. Most individuals (88.9%) had a positive silhouette value, indicating similar kinematic and muscle activity patterns during running. Interestingly, the two excluded subjects had the highest body mass of the group (subject 1: 90 kg, subject 2: 97.7 kg). However, it is currently unknown if and how body mass is linked to the exclusion of these individuals. Most individuals of Group U had negative silhouette values, suggesting that the group members did not share similar kinematic or muscle activity patterns during running. It is speculated that individuals of Group U are not members of one specific functional group, but rather belong to several different functional groups (Figure 5-6).

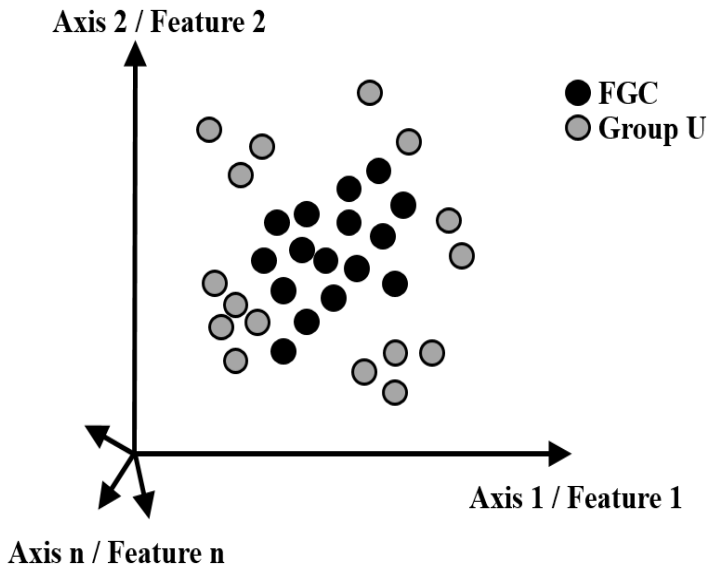


Figure 5-6: Schematic visualizing the functional group (FGC) and the uncomfortable group (Group U) in a multi-dimensional vector-space. Each dot represents one individual member of either FGC (black dots) or Group U (grey dots). It is speculated that the individuals of FGC had similar and group-specific functional solutions, and therefore cluster together in the vector-space. In contrast, Group U contains individuals from different functional groups with diverse biomechanical solutions. Therefore, it is speculated that these individuals scatter around FGC, with only a few of them creating clusters. Thus, ratings of discomfort should not be used to identify functional groups.

Similar to previous research, the running kinematics were significantly different between FGC and Group U (Table 5-3) (Hoerzer et al., 2015b). Additionally, the two groups had different muscle activity patterns to perform the same motor task (Table 5-3). Such different neuromuscular strategies for a running motor task have been reported between barefoot and shod (von Tscharner

et al., 2003) and between males and females (von Tscharner and Goepfert, 2003). To the authors' knowledge, however, this is the first time that differences in neuromuscular strategies have been observed between two (assumingly) homogeneous groups of runners performing the same motor task with the same footwear. The classification rates, however, between these groups were rather small compared to other classification studies (e.g., Begg and Kamruzzaman, 2005). This moderate classification accuracy is likely based on the assumption that Group U contained individuals from different functional groups with diverse biomechanical solutions (Figure 5-6). It can be postulated that these diverse biomechanical solutions made it difficult for the classification algorithm to classify between Group U and FGC.

This study demonstrated a successful approach to identify functional groups in running. Using this approach might enable future studies to develop profiles of various functional groups with respect to their demographic and anthropometric characteristics, biomechanics, and footwear needs. A limitation to this study was that the running speed for the comfort assessment was the subject's preferred speed, while during the biomechanical assessment the speed was controlled for. Another limitation is that the proposed approach requires biomechanical data, which in a practical setting (e.g., sports store) often cannot be fully acquired. However, one important result of this study is that footwear comfort alone seems to provide already a high accuracy (~90%) to identify functional groups. Although this needs to be confirmed by more studies, it appears that comfort ratings are related to functional solutions. Individuals with low comfort ratings, however, exhibit diverse functional solutions and do not belong to a common group. Given the high accuracy (~90%) of grouping by footwear comfort alone, sports stores or sporting goods manufacturer might utilize (high) comfort ratings as a first approach to customize footwear to different athlete groups.

However, research should focus on the development of mobile biomechanical assessment protocols, such as inertial measurement units, to further optimize grouping accuracy. Furthermore, future studies should also aim to better understand how to match footwear constructions to the identified functional groups.

5.5 Conclusion

A functional group is a group of people with similar functional solutions when performing a motor task in a specific footwear. Such groups can be identified by first isolating individuals who choose the same footwear as comfortable and, then excluding all individuals from this group who do not share the same functional (kinematic and EMG) solutions. Utilizing this approach identifies groups with specific functional solutions within a homogenous cohort of athletes.

Chapter Six: Can Footwear Comfort be used to select Footwear for a Functional Group?

6.1 Introduction

In running, shoes and insoles with various constructions and materials have been used to influence human movement (Nigg, 2010). The objective of these footwear interventions is often to improve athletic performance and/or reduce the risk of injuries (Nigg et al., 2015; Madden et al., 2016; Sinclair et al., 2016). A key limitation when using footwear to support human movement during running is that a given footwear construction typically produces different responses for different groups of individuals. Specifically, groups can demonstrate group-specific responses in their biomechanics, physiology, and/or perception with respect to the same insole or shoe construction (Nigg et al., 1998, 2003a; Hoerzer et al., 2015a; Madden et al., 2016; Sinclair et al., 2016). A given running shoe construction, for example, can enhance athletic performance for one group of runners, while decreasing performance for another group (Sinclair et al., 2016). The implication of this observation is that different groups of individuals require different footwear constructions to improve their athletic performance and/or reduce the likelihood of injury.

Groups with similar reactions and footwear needs have been referred to as 'functional groups' (Nigg et al., 1999; Nigg, 2010). Previous research regarding functional groups has primarily focused on providing methodological approaches to identify functional groups. Functional groups, for example, have been identified using pattern recognition techniques to cluster individuals with similar running mechanics (Hoerzer et al., 2015b). In addition, research has shown that functional groups can also be formed by analyzing footwear comfort ratings in combination with biomechanical data (Chapter 5). While there is knowledge about methods to identify functional

groups, there are no studies that provide an understanding of how to match specific footwear constructions to these groups in order for them to benefit with respect to health and/or performance.

Nigg et al. (2015) proposed the 'comfort filter' paradigm, which suggests that individuals can automatically find the shoe/insole combination that is beneficial for them by selecting footwear that they find comfortable. This paradigm is based on research suggesting that using comfortable footwear may enhance running economy (Luo et al., 2009), reduce the frequency of injuries (Mündermann et al., 2001; Kinchington et al., 2011), and may also improve neuromuscular control of balance (Burke, 2012). Based on this comfort filter paradigm, one can speculate that a shoe or insole that is selected as comfortable by a functional group, will be a footwear intervention that can improve performance and/or reduce the risk of injuries within this group. Therefore, using footwear comfort may allow to find footwear constructions that promote health and/or performance of a functional group. If comfortable footwear does benefit a functional group, then one could expect to see not only a significant influence of comfortable footwear on (a) the group's running biomechanics in general, but also on (b) biomechanical variables that have been associated with running injuries and performance. However, this speculation has not yet been tested.

Therefore, the objective of this study was to investigate the effect of comfortable footwear on the kinematics, kinetics, and muscle activation of a functional group during running. The hypotheses to be tested were:

H1: Changing between a comfortable and an uncomfortable footwear condition will significantly change a functional group's lower extremity kinematics, kinetics, and/or muscle activity during running.

H2: Running in a comfortable compared to uncomfortable footwear condition influences biomechanical performance and injury variables in a direction that they would indicate a reduced risk of injuries and/or enhanced performance.

6.2 Methods

To investigate the effect of comfortable footwear on the running biomechanics of a functional group, a previously identified functional group was investigated (Chapter 5). The group's running kinematics, kinetics, and muscle activity data were compared between running with a comfortable footwear condition and an uncomfortable footwear condition.

6.2.1 Functional Group

For a detailed description of how the functional group was identified refer to Chapter 5. Briefly, to identify the group a comfort assessment was conducted with 114 male runners. The tested individuals were between 18 and 50 years of age and in general good health with no pain or injuries with respect to the lower extremity at the time of the testing. One aim of the comfort assessment was to find a group of individuals who selected the same footwear condition as being comfortable. The comfort assessment was conducted on six different test insoles with varying properties placed in the same neutral running shoe (adidas Boston, adidas AG, GER) (Table 6-1). Three comfort assessment sessions were conducted (one familiarization session and two actual testing sessions) on an indoor running track with each subject on three different days. A 150-mm Visual Analog Scale (VAS) with end points being 'Not comfortable at all' and 'Most comfortable insole imaginable' was used by the subjects to rate footwear comfort directly after running in each of the test conditions.

Table 6-1: Properties of the insoles used to create the different test conditions.

Name	Elasticity	Geometry		Hardness		Thickness	
		Arch	Heel	Description	Asker C	Forefoot	Rearfoot
Shaped Soft	Elastic	High	Spherical	Soft	25-35	5 mm	10 mm
Shaped Hard	Elastic	High	Spherical	Hard	60-70	5 mm	10 mm
Flat Soft	Elastic	Flat	Flat	Soft	25-35	5 mm	10 mm
Flat Hard	Elastic	Flat	Flat	Hard	60-70	5 mm	10 mm
Flat Gel	Visco-Elastic	Flat	Flat	Soft	25-35	5 mm	10 mm
Flat Thin	Visco-Elastic	Flat	Flat	Hard	60-70	2 mm	2 mm

After identifying a group who selected the same footwear condition as being comfortable, a biomechanical assessment with this group (n = 18) was performed to exclude individuals whose kinematics and muscle activity patterns while running were different from the rest of the group. This procedure yielded a functional group including 16 individuals (Table 6-2).

Each member of this functional group selected the same footwear condition (the Flat Thin insole) as being comfortable. An uncomfortable footwear condition was also determined for each group member. The uncomfortable condition was the insole with the lowest average comfort rating (based on the two testing days) for each member of the functional group. For one individual,

however, the difference between the comfortable condition and the condition with the lowest comfort rating was only 12 mm on the VAS. Therefore, for this individual, one can doubt if the insole with the lowest rating represented a truly uncomfortable condition. As a result, this member of the functional group was excluded from the subsequent analysis.

Table 6-2: Demographics of the functional group (mean, standard deviation: SD, range)

N	Sex	Age [yrs]	Mass [kg]	Height[cm]
16	Male	30.5 SD 8.3 18-49	75.3 SD 4.3 68.7-82.0	178.2 SD 5.7 167.0-187.5

6.2.2 Biomechanical Data Collection

For the identification of the functional group, a biomechanical assessment was performed (see Chapter 5). During this assessment, data to investigate also the effect of a comfortable and an uncomfortable footwear condition on the running biomechanics of the functional group were collected. The experimental protocol of the biomechanical data collection is described below.

First, subjects completed a brief warm-up that included running at a self-selected pace in a control condition. The control condition was the neutral running shoe used for the comfort assessment with its standard insole. Afterwards, participants were instructed to perform a neutral standing trial and 10 successful heel-toe over ground running trials (speed: 3.5 ± 0.5 ms^{-1}) in both their comfortable and uncomfortable footwear condition. The order of the footwear condition was randomized at each testing session and participants were not informed which condition they

received. The neutral standing trial was used to define joint centers. To perform the running trials successfully, a participant's right foot had to land within the edges of the force platform (Kistler Instrumente AG, Switzerland) that was used to collect ground reaction force (GRF) data (sampling frequency: 2400 Hz). The force plate was in the middle of a 30 m running lane located in the biomechanics lab. A marker-based 3D motion capture system (Motion Analysis Corp., USA) was used to measure the 3D trajectories of 18 markers with a sampling frequency of 240 Hz. The markers were located at the pelvis (right and left anterior and posterior superior iliac spine), at the right thigh (greater trochanter; and at a proximal, lateral, and distal position), at the right knee (lateral and medial epicondyle), at the right shank (at a proximal, lateral, and distal position), at the right ankle (medial and lateral malleoli), and at the right shoe (at a distal and proximal heel position; at the head of the 5th metatarsal bone). This marker set was an extension of the marker set used in Chapter 5, and was chosen to be able to calculate gait variables, such as joint angles and joint angular velocities (Table 6-3).

The activity of five major muscles of the right lower-extremity (Table 6-3) was measured using surface electromyography (EMG) with bipolar Ag/AgCl surface electrodes (Norotrode dual electrodes, Myotronics Inc., USA) at a sampling frequency of 2400 Hz. SENIAM recommendations were used to place the electrodes on the bellies of the muscles (Hermens et al., 1999) with the ground electrode located at the tibial tuberosity. Before placing each electrode, the skin was carefully prepared by shaving the hair, slightly abrading it with sand paper, and finally cleaning it with isopropyl wipes. Medical tape was used to secure the electrodes, cables, and amplifiers to reduce potential motion artifacts in the signals. The kinematics, GRFs, and muscle

activity data of the right lower extremity during the foot strike that landed on the force platform were used for subsequent analysis.

Table 6-3: Time-continuous variables (waveforms) investigated in this study. All kinematic and kinetic variables were computed for all three planes of motion: sagittal, frontal, and transverse.

Variable	**Segment/Muscle**		
Joint Angles [°]	Hip	Knee	Ankle
Joint Angular Velocities [°s^{-1}]	Hip	Knee	Ankle
Joint Moments [BWm]	Hip	Knee	Ankle
Ground Reaction Force [BW]			
EMG Total Intensity [norm. to MVC]	Vastus Lateralis (VL)	Rectus Femoris (RF)	Biceps Femoris (BF)
	Gastrocnemius Medialis (GM)	Tibialis Anterior (TA)	

6.2.3 Data Pre-Processing

Cortex 3 (Motion Analysis Corp., USA) was used to reconstruct the 3D marker trajectories for both the standing and running trials. For the running trials, markers located at the greater trochanter, knee, and ankle were neglected for the analysis. A standard motion analysis software (Visual 3D, C-Motion Inc., USA) was utilized to further process the marker trajectories and GRFs to compute time-continuous gait variables (Table 6-3). Kinematic data and GRF data, when used for inverse dynamics calculation, were filtered using a fourth-order, low-pass, Butterworth filter with the same cut-off frequency of 12 Hz (Bisseling and Hof, 2006). Separately analyzed GRF

data were filtered with a cut-off frequency of 50 Hz. Kinematic and kinetic waveforms were time-normalized to represent 0 to 100% (101 data points), where 0% represented the initial heel-strike and 100% toe-off. The force threshold to identify heel-strike and toe-off in the vertical GRF was set at 20 N. Kinetic variables were normalized to body weight.

The raw EMG signals obtained from the electrodes were pre-amplified and filtered using a band-pass filter with a lower cutoff frequency of 10 Hz and an upper cutoff frequency of 500 Hz. The raw EMG data were then processed using a wavelet analysis (von Tscharner, 2000). To this purpose, the raw EMG signals were transformed to time-frequency space using 13 non-linear wavelets (center frequencies: 6.9-542 Hz). The raw EMG signals and the EMG signal resolved in time-frequency space were carefully inspected for other measurement noise. Afterwards, wavelets 3 to 11 were summed at each time point to obtain an EMG total intensity waveform. The four wavelets that were not included in the EMG waveform (i.e., 1, 2, 12, and 13) often contain motion artifacts or measurement noise (von Tscharner, 2000; Nigg and Gérin-Lajoie, 2011). The EMG total intensity waveforms were then normalized with respect to amplitude and time. For the amplitude-normalization, isometric maximum voluntary contractions (MVCs) of each muscle were performed by each subject and recorded using a computerized dynamometer (System 3 Pro, Biodex Medical Systems, USA). The MVCs were measured using a standard protocol, which was similar to the one executed by Albertus-Kajee et al. (2011). MVCs were performed in a sitting position with the following joint angles: 60° knee flexion for RF, VL, and BF measurements; 30° knee flexion and 0° ankle flexion for TA and GM measurements. The EMG total intensity waveforms were then normalized to the maximum EMG total intensity obtained during these contractions. EMG waveforms were time-normalized to represent two time windows with a total

of 201 data points. The length of both time windows was defined by the duration of the stance phase (i.e., 0% = heel-strike; 100% = toe-off; -100% ~ mid-swing). In order to identify and exclude potential outliers, a Grubbs test was performed ($\alpha = 0.01$) based on the peak value of each EMG total intensity waveform (Grubbs, 1969). Using the EMG total intensity waveforms, the activity of each muscle could be investigated. This could be done by either analyzing the waveforms as they are, or integrating the waveforms to determine activity for the entire or specific phases of the stance phase (e.g., muscle activity during propulsion). Hence, the integration of an EMG total intensity waveform was referred to as the 'Muscle Activity'.

6.2.4 Data Analysis and Statistics

To analyze if there was a significant impact on the running biomechanics in general when using comfortable footwear, an analysis approach based on time-continuous variables was used (Table 6-3). This method provided the advantage of analyzing all the data of the collected kinematic, kinetic, or EMG waveforms, without neglecting data that may contain differences between the footwear conditions (Nigg, 2010). For each variable, an input matrix was defined containing the 101 (kinematics and kinetics) or 201 (EMG) data points of this variables (columns of the matrix) and the corresponding individual trials performed by all subjects (rows of the matrix) in both footwear conditions. For each variable, a Support Vector Machine (SVM) was utilized with the corresponding input matrix to compare the data of the footwear conditions (Vapnik, 1995). The outcome of the SVM for each variable was a classification rate, indicating how well the data (i.e., trials) of the two footwear conditions could be classified. Finally, an one-sided binomial test ($\alpha = 0.05$) was used to determine if a classification rate was high enough to reach statistical significant differences between footwear conditions (Hoerzer et al., 2015b).

To investigate whether the comfortable footwear condition influenced variables that have previously been related to running injuries and/or running performance, an analysis approach using standard, time-discrete variables was utilized. First, variables linked to running injuries and running performance (or economy) were identified based on previous research (Table 6-4). Afterwards, a paired sample t-test ($\alpha = 0.05$) was utilized to compare these time-discrete variables between the footwear conditions. In addition, the effect size for each variable was computed using Cohen's d.

Table 6-4: Time-discrete variables that have been associated with running injuries or running performance/economy in previous studies. The listed injury variables were linked to an increased risk of running injuries. All mentioned performance variables were associated with enhanced running performance or running economy.

Increased Risk of Running Injuries		
Variable	**Injury Type**	**Reference and Sample Size (n)**
Ground Reaction Force: Increased Vertical Impact Peak [BW]	No Injury Type Specified	Hreljac et al. (2000) (n=24)
Ground Reaction Force: Increased Maximum Vertical Loading Rate [BW/s]	No Injury Type Specified	Bredeweg et al. (2013) (n=77) Hreljac et al. (2000) (n=24)
Ankle Angle: Reduced Eversion Range of Motion [°]	Several Injury Types	Kuhman et al. (2016) (n=19)
Ankle Angle: Increased Peak Eversion Angle [°]	Several Injury Types	Kuhman et al. (2016) (n=19)
Ankle Angular Velocity: Reduced Peak Eversion Velocity [$°s^{-1}$]	Several Injury Types	Kuhman et al. (2016) (n=19)

Ankle Angular Velocity: Increased Peak Eversion Velocity [°s^{-1}]	Several Injury Types	Dudley et al. (2017) (n=31)
Knee Angle: Reduced Flexion Range of Motion (Heel-Strike to Mid-Stance) [°]	Achilles Tendinopathy	Azevedo et al. (2009) (n=42)
Knee Angle: Increased Adduction at Time of the Impact Force Peak [°]	Iliotibial Band Syndrome	Noehren et al. (2014) (n=34)
Knee Moment: Increased Maximum Abduction Moment [BWm]	Several Injury Types	Dudley et al. (2017) (n=31)
Knee Angular Impulse: Increased Angular Abduction Impulse [BW%Stance Phase]	Patellofemoral Pain	Stefanyshyn et al. (2006) (n=40/n=80)
Hip Angle: Reduced Peak Flexion Angle [°]	Patellofemoral Pain	Neal et al. (2016) (Review Paper)

Hip Angle: Increased Internal Rotation Angle at Time of Impact Force Peak [°]	Iliotibial Band Syndrome	Noehren et al. (2014) (n=34)
Hip Angle: Increased Peak Internal Rotation Angle [°]	Patellofemoral Pain	Neal et al. (2016) (Review Paper)
Hip Angle: Increased Peak Adduction Angle [°]	Patellofemoral Pain	Neal et al. (2016) (Review Paper)

Enhanced Running Performance/Economy

Variable	**Reference and Sample Size (n)**
Ankle Angle: Decreased Plantarflexion at Toe-Off [°]	Moore (2016) (Review Paper)
Knee Angle: Decreased Flexion (Extension) Range of Motion [°]	Folland et al. (2017) (n=97)

Knee Angle: Decreased Extension at Toe-Off [°]	Moore (2016) (Review Paper)
Knee Angle: Increased Maximum Knee Flexion [°]	Folland et al. (2017) (n=97)
Hip Angle: Decreased Flexion Range of Motion [°]	Folland et al. (2017) (n=97)
Vastus Lateralis: Decreased Muscle Activity during Propulsion	Moore (2016) (Review Paper)
Rectus Femoris: Decreased Muscle Activity during Propulsion	Moore (2016) (Review Paper)
Biceps Femoris: Decreased Muscle Activity during Propulsion	Moore (2016) (Review Paper)
Tibialis Anterior: Decreased Muscle Activity during Propulsion	Moore (2016) (Review Paper)

Gastrocnemius Medialis: Moore (2016) (Review Paper)

Decreased Muscle Activity during Propulsion

6.3 Results

The mean rating of the comfortable footwear condition was 121.3 ± 10.7 mm (mean ± SD), and 41.9 ± 22.4 mm for the uncomfortable footwear condition (Figure 6-1). There was a significant difference between the ratings of these footwear conditions ($p<0.001$, Cohen's $d = 4.53$). The footwear condition that was rated as not comfortable varied among the individuals of the functional group. The following conditions were chosen as not comfortable: 7 x Flat Hard, 5 x Shaped Hard, 2x Shaped Soft, and 1 x Flat Gel.

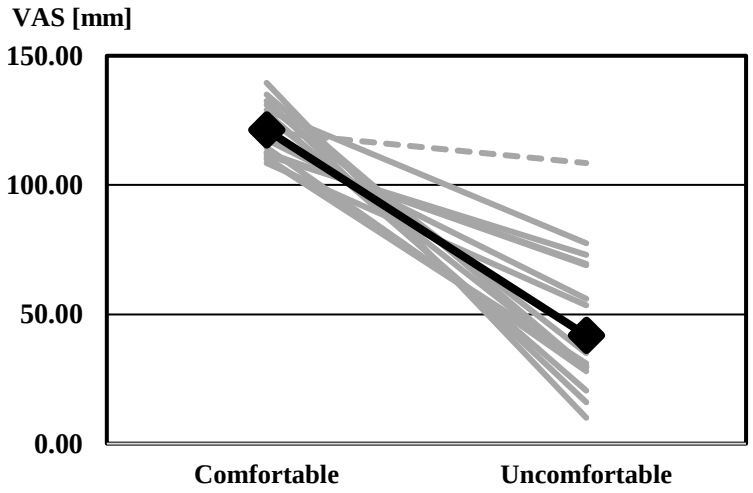


Figure 6-1: The Visual Analog Scale rating (0 mm = 'Not comfortable at all'; 150 mm = 'Most comfortable insole imaginable) for the footwear conditions selected as comfortable and uncomfortable. Grey lines represent the mean rating of each individual subject. Grey dotted line represents the subject that was excluded from this study. The black line shows the mean (without the excluded subject) comfort rating for a footwear condition. The comfortable footwear condition was the same for all participants; the uncomfortable footwear condition varied among the subjects.

Significant differences between the comfortable and uncomfortable footwear conditions were found in the kinematics, kinetics, and EMG data during running (Table 6-5). Significant differences between the footwear conditions were also obtained for time-discrete variables that have been associated with running injuries and running performance/economy (Table 6-4, 6-6). The absolute effect size (Cohen's d) of the significant variables ranged from 0.20 to 0.86. One of the five significant different injury variables indicated a beneficial effect for injury prevention with the comfortable footwear. All other significant injury variables suggested a disadvantageous effect when running with the comfortable footwear condition. For running performance, the two variables with significant footwear differences suggested a disadvantage of the comfortable footwear condition. For example, the increased ankle plantarflexion angle at toe-off was one of the variables that indicated reduced performance when running with the comfortable footwear condition (Figure 6-2; Table 6-4).

Table 6-5: Classification rates and p-values for the comparison between comfortable and uncomfortable footwear condition using time-continuous variables in combination with a Support Vector Machine. Variables with significant differences between the footwear conditions are bold.

Kinematics

Angle	**Sagittal**	**Frontal**	**Transverse**
Ankle	**60.7 % (p<0.001)**	**66.3 % (p<0.001)**	51.3 % (p=0.343)
Knee	**56.3 % (p=0.016)**	**56.0 % (p=0.022)**	49.3 % (p=0.614)
Hip	53.3 % (p=0.136)	**61.7 % (p<0.001)**	54.3 % (p=0.074)
Velocity	**Sagittal**	**Frontal**	**Transverse**
Ankle	**60.0 % (p<0.001)**	**62.7 % (p<0.001)**	**61.3 % (p<0.001)**
Knee	**60.3 % (p<0.001)**	53.3 % (p=0.136)	50.0 % (p=0.523)
Hip	**59.0 % (p=0.001)**	53.7 % (p=0.113)	49.7 % (p=0.569)

Kinetics

GRF	**Anterior/Posterior**	**Medial/Lateral**	**Vertical**
	62.0 % (p<0.001)	**58.3 % (p=0.002)**	**62.0 % (p<0.001)**
Moment	**Sagittal**	**Frontal**	**Transverse**
Ankle	**61.7 % (p<0.001)**	**63.3 % (p<0.001)**	**65.3 % (p<0.001)**
Knee	**61.0 % (p<0.001)**	**59.7 % (p<0.001)**	**59.0 % (p=0.001)**
Hip	**59.3 % (p<0.001)**	**56.0 % (p=0.022)**	**61.0 % (p<0.001)**

EMG Data

Vastus Lateralis	Rectus Femoris	Biceps Femoris
49.7 % (p=0.57)	52.3 % (p=0.25)	**61.2 % (p<0.001)**
Tibialis Anterior	Medial Gastrocnemius	
53.3 % (p=0.14)	**60.7 % (p<0.001)**	

Table 6-6: Mean, standard deviation (SD), p-value, and effect-size (Cohen's d) for the comparison between the comfortable and uncomfortable footwear conditions. For the comparison, time-discrete variables that have previously been associated with running injuries and running performance/economy were analyzed: p-values that represented significant differences are bold; * indicates if a variable with significant difference indicated a reduced injury risk or improved running performance/economy with the comfortable footwear condition.

Increased Risk of Running Injuries **Variable**	**Comfortable**	**Uncomfortable**	**p-value**	**Cohen's d**
Ground Reaction Force: Increased Vertical Impact Peak [BW]	1.43 SD 0.20	1.41 SD 0.19	0.46	0.08
Ground Reaction Force: Increased Maximum Vertical Loading Rate [BW/s]	74.86 SD 15.54	63.16 SD 11.30	**<0.001**	0.86
Ankle Angle: Reduced Eversion Range of Motion [°]	14.43 SD 3.39	14.27 SD 3.45	0.72	0.05
Ankle Angle: Increased Peak Eversion Angle [°]	9.01 SD 2.15	8.45 SD 2.51	0.23	-0.24
Ankle Angular Velocity: Reduced Peak Eversion Velocity [$°s^{-1}$]	317.37 SD 81.24	279.21 SD 74.27	**0.02***	-0.49

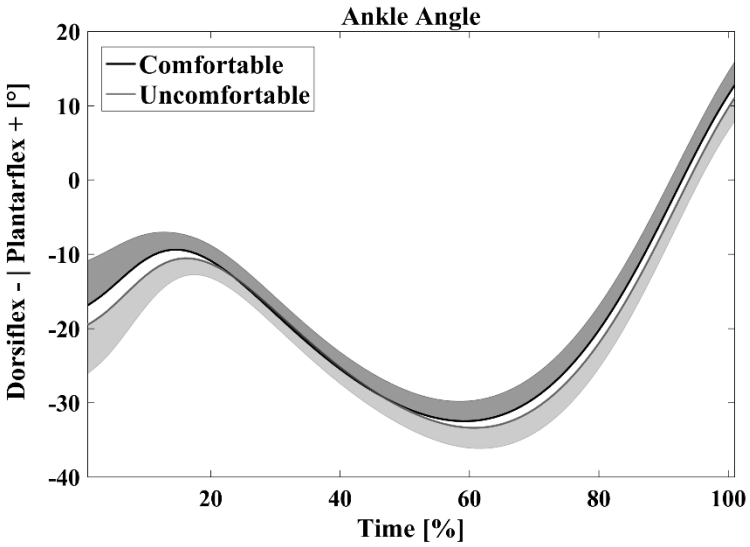
Ankle Angular Velocity: Increased Peak Eversion Velocity [°s^{-1}]	317.37 SD 81.24	279.21 SD 74.27	**0.02**	-0.49
Knee Angle: Reduced Flexion Range of Motion (Heel-Strike to Mid-Stance) [°]	31.01 SD 2.99	32.03 SD 3.46	0.06	-0.32
Knee Angle: Increased Adduction at Time of the Impact Force Peak [°]	-2.29 SD 3.52	-3.34 SD 3.56	**0.02**	0.30
Knee Moment: Increased Maximum Abduction Moment [BWm]	0.71 SD 0.34	0.69 SD 0.37	0.66	-0.05
Knee Angular Impulse: Increased Angular Abduction Impulse [BW%Stance Phase]	29.01 SD 17.60	28.46 SD 18.95	0.75	-0.03
Hip Angle: Reduced Peak Flexion Angle [°]	50.59 SD 6.14	50.55 SD 5.99	0.92	-0.01
Hip Angle: Increased Internal Rotation Angle at Time of Impact Force Peak [°]	-7.23 SD 6.59	-8.92 SD 7.07	**0.03**	0.25
Hip Angle: Increased Peak Internal Rotation Angle [°]	-1.38 SD 6.79	-2.59 SD 7.12	0.09	0.17

Hip Angle: Increased Peak Adduction Angle [°]	11.50 SD 3.31	11.33 SD 3.45	0.46	0.05

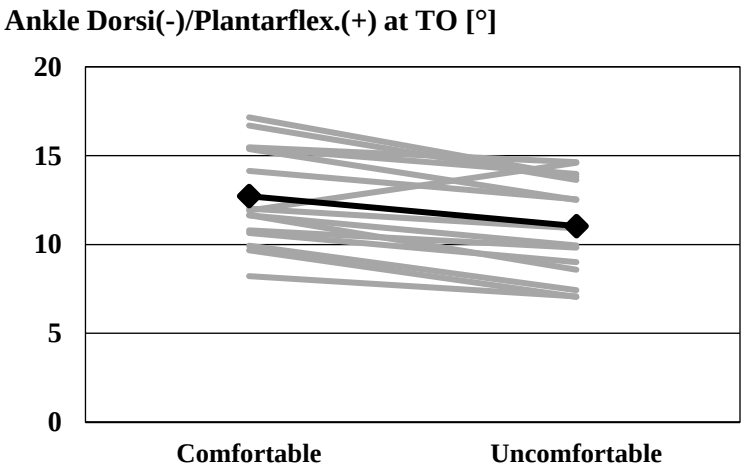
Enhanced Running Performance/ Economy

Variable	Comfortable	Uncomfortable	p-value	Cohen's d
Ankle Angle: Decreased Plantarflexion at Toe-Off [°]	12.72 SD 2.78	11.04 SD 2.81	**0.001**	0.60
Knee Angle: Decreased Flexion (Extension) Range of Motion [°]	33.29 SD 3.72	33.51 SD 3.94	0.61	-0.06
Knee Angle: Decreased Extension at Toe-Off [°]	-23.12 SD 4.17	-23.17 SD 4.55	0.93	-0.01
Knee Angle: Increased Maximum Knee Flexion [°]	54.45 SD 3.54	54.65 SD 4.18	0.64	-0.05
Hip Angle: Decreased Flexion Range of Motion [°]	49.46 SD 4.54	49.59 SD 4.32	0.84	-0.03
Vastus Lateralis: Decreased Muscle Activity during Propulsion	4.69 SD 3.25	4.03 SD 3.25	0.37	0.20

Rectus Femoris: Decreased Muscle Activity during Propulsion	1.46 SD 0.76	1.46 SD 0.76	0.99	0.00
Biceps Femoris: Decreased Muscle Activity during Propulsion	13.45 SD 8.48	11.76 SD 8.18	**0.036**	0.20
Tibialis Anterior: Decreased Muscle Activity during Propulsion	4.34 SD 2.63	3.74 SD 1.35	0.30	0.28
Gastrocnemius Medialis: Decreased Muscle Activity during Propulsion	35.81 SD 22.03	38.42 SD 23.49	0.32	-0.11



(a)



(b)

Figure 6-2: (a) Mean (+ or – standard deviation) ankle dorsiflexion (-) and plantarflexion (+) angle during the stance phase of running. (b) Ankle dorsiflexion and plantarflexion angle at toe-off (TO). Grey lines represent the mean angle of each individual subject. The black line shows the mean angle of each footwear condition.

6.4 Discussion

The findings of this study demonstrated that changing between a comfortable and an uncomfortable footwear condition significantly impacts the running biomechanics of a functional group. This outcome supported the first hypothesis of the study. In addition, running in a comfortable footwear condition influenced biomechanical variables that had previously been associated with running injuries and/or running performance. The majority (6 out of 7) of these injury or performance variables, however, changed in a direction that they would suggest an increased likelihood of running injuries and reduced running performance. Hence, the second hypothesis of this study had to be rejected. Consequently, this study's attempt to further support previous research suggesting that footwear comfort can be used to identify footwear constructions that benefit a functional group was not successful.

The "Flat Thin" insole was the comfortable footwear condition for all members of the functional group. In contrast, the condition that was selected as not comfortable was different for different group members. Different group members choosing different footwear constructions as not comfortable might have caused the larger standard deviation of the VAS ratings for the uncomfortable condition (SD: 22.4 mm) compared to the comfortable condition (SD: 10.7 mm). Although the uncomfortable condition varied among subjects, common properties among these insoles could be identified. In fact, 12 out of 15 participants selected insoles that consisted of a hard, elastic material and were thicker than the "Flat Thin" insole. Therefore, these specific properties seem to be perceived as uncomfortable by the members of the functional group and, therefore, should be avoided when selecting running footwear for this group.

Footwear comfort is a multifactorial variable, which has been suggested to be influenced by mechanical, neurophysiological, and psychological factors (Mills et al., 2010). Therefore, it has been speculated that a change in footwear comfort perception can explain a change in the biomechanics of an individual during locomotion. This study revealed differences in time-continuous biomechanical variables between running in a comfortable and an uncomfortable footwear condition (Table 6-5). This outcome is similar to previous research that has shown differences in time-discrete biomechanical variables between comfortable and uncomfortable footwear constructions during locomotion (Chen et al., 1994; Mündermann et al., 2003). Thus, the current study supported the assumption that footwear comfort perception is associated with biomechanical adaptions. In fact, footwear comfort seems to holistically impact the human locomotor system by influencing different types of biomechanical variables related to different body segments (e.g., knee angles, ankle moments, etc.), as seen in the current study (Table 6-5). A holistic effect of footwear comfort on a combination of kinematic, kinetic, and EMG variables was also revealed by Mündermann et al. (2003). The significant classification rates in the current study were rather low (56.0-66.3%). This may suggest a moderate influence of footwear comfort on running biomechanics. This moderate impact of footwear comfort was supported by the calculated effect sizes (mean absolute effect size: 0.46) of the discrete variables with significant differences between the footwear conditions (Table 6-6). Therefore, footwear comfort seems to have a moderate, but significant impact on the biomechanics during running.

It was speculated that footwear comfort does not only affect the biomechanics of a functional group in general, but also influences variables that have been associated with running injuries or performance (Table 6-4). Specifically, it was hypothesized that using a comfortable footwear

condition influences these biomechanical variables in a direction that they would indicate a reduced risk of injuries and/or enhanced running performance/economy. Five injury variables and two performance variables revealed significant differences between the footwear conditions. However, most of these variables (four injury variables and all performance variables) changed in a direction that they may suggest an increased injury risk and a reduced running performance with the comfortable footwear condition (Table 6-6). This outcome potentially proposes that the comfortable footwear condition did not support the functional group's locomotor system.

There might be two possible reasons that may explain the study outcome that comfortable footwear does not seem to benefit the human body during locomotion. One reason, and the main limitation of this study, was that running injuries and running performance/economy were not directly measured. In fact, time-discrete biomechanical variables were analyzed with the purpose to make predictions about performance and injuries during running. Although it was speculated that this would provide a first understanding about the impact of comfortable footwear on health and performance of a functional group, the accuracy of these variables to actually predict injuries or performance might be limited. Especially for studies examining running injuries, many study designs have limitations such as being cross-sectional and including small cohorts. For example, studies that correlated the maximum vertical loading rate (Hreljac et al., 2000), peak ankle eversion velocity (Kuhman et al., 2016; Dudley et al., 2017), and knee adduction and internal hip rotation angle at time of impact (Noehren et al., 2014) to running injuries had rather small sample sizes ($n < 35$), reducing the statistical power of these studies and their findings. Additionally, some of these studies identified the injury variables by retrospectively comparing injured and non-injured groups (Hreljac et al., 2000; Noehren et al., 2014). Such retrospective study designs do not allow for the

determination of causal relationships and, therefore, limit the prediction accuracy of the identified variables in these studies. Overall, little is known in which cases variables are injury or performance predictors. Therefore, although the current study may provide a first understanding, no conclusive statements about the effect of comfortable footwear on injury and performance can be made. Consequently, there is a need for future studies that directly measure running performance and injuries to investigate the effect of comfortable footwear on the locomotor system of functional groups during running.

Another probable reason explaining the current study findings may be the theoretical possibility that, indeed, comfort cannot be used to identify the footwear that is beneficial for a functional group. Thus, methods based on biomechanical and physiological variables might be required to select the correct footwear for a functional group. Future studies are therefore needed to better understand how footwear influences the running biomechanics of a functional group, such as the impact of different footwear constructions on the group's preferred movement path (Nigg et al., 2015). This knowledge might be the basis for biomechanical methods supporting not only the identification of beneficial footwear constructions, but also aid the development of new innovative footwear features.

Nigg et al. (2015) has proposed that an individual automatically selects the footwear construction that is beneficial for her/him by utilizing their individual comfort filter. It was therefore speculated that by quantifying footwear comfort, one can identify the footwear construction that supports a functional group's locomotor system during running. This study was a first attempt to investigate if, indeed, footwear comfort can be used to select footwear for functional groups. The two main

results of this study were that (a) footwear comfort changes biomechanical variables, and (b) the attempt to relate these changes to possibly supportive effects for running injury or performance was not successful.

6.5 Conclusion

Comfortable footwear significantly influences the lower-extremity biomechanics of a functional group during running. The attempt to use biomechanical injury and performance variables to support the assumption that footwear comfort has a beneficial effect and, therefore, can be used to select footwear for functional groups was not successful. Future studies are required that directly measure running injuries and performance to make more conclusive statements about footwear comfort and its ability to identify footwear constructions that promote health and performance of different functional groups.

Chapter Seven: Summary and Conclusion

Footwear is frequently used in sports to support human movement (Nigg, 2010). For running, footwear has been developed with the aim to make runners faster and/or to reduce their risk of sustaining injuries (Nigg et al., 2015; Sinclair et al., 2016). A key challenge in the development of footwear that benefits performance and/or runner health is that different individuals react to the same footwear intervention differently with respect to their biomechanics, physiology, and/or perception (e.g., Bates et al., 1983; Mündermann et al., 2002; Nigg et al., 2003a, 2003b; Roy and Stefanyshyn, 2006; Sinclair et al., 2016). The important consequence of this observation is that a footwear construction that promotes performance and/or health for one runner, may be ineffective or even detrimental for another runner. Runners with similar reactions to a specific footwear intervention can be grouped. It was speculated that the identification of such 'functional groups' might be an approach to address the different reactions of different people to footwear constructions (Nigg, 2010). Furthermore, it was speculated that the identification of functional groups may help in the selection of appropriate footwear.

For this doctoral thesis, a functional group was defined as a group of individuals with the same group-specific functional (biomechanical and/or physiological) solutions when performing a locomotion task with a specific footwear. Specifically, it was hypothesized that runners in the same functional group would have similar functional solutions while running and, therefore, similar reactions to a given footwear intervention. Therefore, matching footwear constructions to the specific functional solutions of a functional group was assumed to cause the same positive and/or negative effects for all group members. In order to test this hypothesis, a methodology to identify functional groups needed to first be developed. Therefore, the main objective of this doctoral thesis

was to develop and test methods to identify functional groups for running footwear. Specifically, this thesis tried to answer the following specific research questions:

1. Can pattern recognition techniques be used to identify functional groups?
2. How reliable are footwear-related comfort assessments?
3. Can footwear comfort be used to identify functional groups?
4. Can footwear comfort be used to select beneficial footwear for a functional group?

7.1 Can pattern recognition techniques be used to identify functional groups?

Groups with group-specific biomechanical characteristics are often identified by simply pre-grouping individuals based on specific characteristics, such as age or gender (e.g., Ferber et al., 2003; Chumanov et al., 2008; Fukuchi and Duarte, 2008). This approach has the limitation that it must be known which characteristics cause differences in biomechanical variables in order to pre-group the individuals. Pattern recognition techniques have the capability to automatically identify groups that have similar and group-specific data. Therefore, if functional groups exist, pattern recognition techniques might have the capability of identifying functional groups based on their group-specific biomechanical solutions. Hence, the main objective of the first study of this PhD research was to propose and test a methodological approach to identify functional groups with group-specific movement patterns using Self-Organizing Maps (and *k*-means clustering algorithms) and Support Vector Machines. These pattern recognition techniques were applied to a data set that included the running kinematics of 45 healthy males and 43 healthy females (16-76 years). The data set also contained footwear comfort ratings for running shoes with different midsole hardness properties.

Eight groups with group-specific movement patterns were identified by the pattern recognition approach. Some of these groups had differences in their comfort preferences for running shoes with different midsole hardness properties. Thus, functional groups could be revealed with group-specific movement patterns and footwear comfort requirements. In addition, some of the groups with differences in their movement patterns and footwear requirements had no differences in age or gender.

In this part of the doctoral thesis, a pattern recognition approach was successfully used to automatically identify functional groups based on their movement patterns. Some functional groups differed in their footwear requirements, but did not have differences in age or gender. This outcome suggested that age and gender are criteria that can separate groups with distinct biomechanics while running, but may not necessarily be the right criteria to identify functional groups with specific footwear requirements. This conclusion emphasizes the importance of the proposed pattern recognition approach to identify functional groups.

7.2 How reliable are footwear-related comfort assessments?

Enhancing footwear comfort has been suggested to potentially improve running performance (Luo et al., 2009), may be associated to improved neuromuscular control of balance (Burke, 2012), and is suggested to reduce the frequency of movement-related injuries (Mündermann et al., 2001; Kinchington et al., 2011). Therefore, in this thesis it was speculated that individuals with the same preferences for comfortable footwear will have (a) the same biomechanical and/or physiological responses to a given footwear condition, and (b) the same needs with regards to footwear constructions. Consequently, individuals that feel comfortable with the same footwear

construction may form a functional group. It was assumed that footwear comfort assessments, therefore, can be utilized to identify functional groups. However, the ability of individuals to assess footwear comfort was unknown. Understanding an individual's footwear comfort assessment reliability is important because unreliable comfort ratings are confounders when using footwear comfort to identify functional groups. Therefore, the objective of the second study of this dissertation was to determine the intra-rater reliability of footwear comfort assessments. Three comfort assessment sessions (1x familiarization session, 2x data collection sessions) were conducted with each of the 90 study participants. During each session, participants performed running trials to assess the comfort of six different shoe insoles by means of Visual Analog Scales (VASs) and 'Yes-No' questions. Intra-class correlation coefficients (for VASs) and Cronbach's alpha values (for 'Yes-No' questions) were calculated to determine intra-rater reliability of the footwear comfort assessments.

Twenty-eight out of the 90 study participants (31.1%) were reliable in assessing footwear comfort based on the VAS. Using 'Yes-No' questions, 42 out of 90 participants (46.7%) had a reliable comfort assessment.

The outcome of this study was that most of the tested individuals were not able to assess footwear comfort in a reliable manner. The reason for this poor reliability remains unclear. Therefore, when using footwear comfort in scientific research projects (e.g., to identify functional groups), one needs to account for this low reliability of comfort assessments. This may be done by (1) simplifying the measure used to assess comfort, (2) only selecting individuals that were pre-tested

for reliable assessments, and/or (3) establishing mean comfort ratings for an individual across multiple testing sessions.

7.3 Can footwear comfort be used to identify functional groups?

In this thesis it was speculated that a shoe is comfortable because it supports a person's functional solution (Mündermann et al., 2001; Luo et al., 2009). Consequently, if one member of a functional group selects a footwear condition as comfortable, all other members that have similar functional solutions should also find that condition comfortable. Therefore, the objective of the third study of this PhD research was to test if functional groups with similar, group-specific functional solutions can be identified using the following analytical steps:

1. Selecting a group of individuals who chose the same footwear as comfortable, and
2. Excluding all individuals from this group wo exhibit functional solutions that are different from the rest of the group.

To test this proposed methodology, first a comfort assessment was conducted with 114 male healthy individuals (age: 28.6 ± 7.1 years, height: 1.79 ± 0.05 m, mass: 76.8 ± 8.3 kg; mean ± standard deviation) to identify one group (Group C) who selected a given footwear condition as comfortable and another group (Group U) who chose the same footwear condition as uncomfortable. Afterwards, a biomechanical assessment was performed with each group (Group C: n=18: Group U: n=17) that included collecting lower-extremity kinematics and muscle activity data during running. Using this data, the functional solutions within and between the groups were compared.

Sixteen out of 18 individuals (89%) from Group C had similar kinematics and muscle activity data while running. These individuals were identified as the functional group. In contrast, most individuals of Group U differed in their kinematics and muscle activity data. Additionally, significant differences in the functional solutions between the functional group and Group U were found.

The outcome from this study revealed that functional groups can be identified by first, isolating individuals who chose the same footwear as comfortable and, second, excluding all individuals from this group who do not share the same functional (kinematic and EMG) solutions. Utilizing this approach successfully revealed functional groups with specific functional solutions within a homogenous cohort of athletes.

7.4 Can footwear comfort be used to select beneficial footwear for a functional group?

While there is now an understanding of methodological approaches to identify functional groups (Chapters 3 and 5), little is known about how to match beneficial footwear constructions to these groups. Nigg et al. (2015) proposed the "comfort filter" paradigm. This paradigm suggests that individuals can automatically find the shoe/insole combination that is beneficial for them by selecting footwear that they find comfortable. Thus, using footwear comfort assessments of a functional group may result in finding footwear constructions that promote their health and/or performance. Therefore, the objective of this study was to investigate if footwear comfort can be used to select footwear for functional groups by investigating the effect of comfortable footwear on the kinematics, kinetics, and muscle activity of a functional group during running. To answer this research question, the previously identified functional group from Chapter 5 was tested. This

functional group contained 16 healthy male subjects between 18 and 49 years of age. The group's lower extremity running kinematics, kinetics, and EMG data were compared between running in a comfortable and an uncomfortable footwear condition. Comparisons were done using (a) time-continuous variables and (b) time-discrete biomechanical injury and performance variables. The idea of the time-discrete biomechanical injury and performance variables was that there are publications that identified variables that were thought to be predictors of injury and/or performance and that the changes in these variables could be discussed with respect to the possible effects of the footwear changes. This assumption, however, was not well supported by the published data since most publications identifying the effect on injuries or performance have rather small sample sizes and the understanding of predicting variables is rather weak. Consequently, these comparisons must be considered with caution.

Significant differences between the comfortable and uncomfortable footwear conditions were found in both the time-continuous kinematic, kinetic, and EMG data, as well as the time-discrete biomechanical performance and injury variables. For the time-discrete analysis, six out of seven biomechanical variables with significant differences changed in a direction that corresponded to an increased injury risk and/or a reduced performance with the comfortable footwear. However, as mentioned before, this result is in the view of the author not strongly supported by conclusive scientific evidence and more work is needed to better understand this complex question. The fact is that it has been shown that comfortable footwear improves performance (Luo et al., 2009) and that comfortable insoles reduce injuries in soldiers substantially (Mündermann et al., 2001), which is in contradiction to the above finding (six out of seven).

The last study of this doctoral thesis revealed that changing from a comfortable to an uncomfortable footwear condition significantly influences the running biomechanics of a functional group. However, the attempt to use time-discrete biomechanical injury and performance variables to support the assumption that beneficial footwear for functional groups can be selected using footwear comfort was not successful. The main reason for this unsuccessful attempt was the fact that biomechanical variables predicting injury and performance have not been conclusively identified in the literature.

7.5 Future Directions

The objective of this dissertation was to develop and test methodological approaches to identify functional groups. While the tested methods successfully identified functional groups, future studies are required to overcome existing limitations of these methodological tools. The first method to identify functional groups utilized pattern recognition techniques. Limitations of this method were associated with the definition of the optimal number of functional groups in a given data set. Currently, the optimal number of groups is determined by a procedure that relied on intuitively and arbitrarily selected variables (e.g., a minimum classification rate). In other words, there is currently no objective procedure available to determine how many functional groups exist within a given data set. Therefore, future research is required to develop such objective procedures to determine the optimal number of groups. Such procedures would further enhance the ability of pattern recognition techniques to identify functional groups. In addition, the pattern recognition tools in this study were applied to 3D marker trajectories recorded during running trials. However, the proposed pattern recognition approach is not limited to kinematic data or running. In the future, data sets including other bio-signals (e.g., kinetic or muscle activity data) recorded during other

motor tasks (e.g., walking) should be analyzed to identify functional groups. The second proposed methodology to identify functional groups was based on footwear comfort in combination with a biomechanical analysis. Since footwear comfort is the key variable of this method, future work should focus on solving the challenges associated with quantifying footwear comfort. For example, one needs to better understand why certain individuals cannot reliably assess footwear comfort, and which strategies are useful to account for this poor intra-rater reliability. Moreover, with the proposed method of combining footwear comfort and biomechanical variables, only one functional group was identified. Therefore, more studies should be conducted utilizing this method to confirm its ability to identify functional groups.

Although the tested identification methods have certain limitations, these methods can already be utilized to obtain more valuable insights about functional groups. Specifically, by using the proposed methods, future research about functional groups may focus on the following tasks:

1. Identifying a collection of different functional groups.
2. Interpreting the specific functional solutions (e.g., movement patterns, muscle activity patterns, etc.) and biological characteristics (e.g., anthropometric data, demographic data, etc.) of the identified functional groups.
3. Matching footwear constructions to the functional solutions of the identified functional groups.

By utilizing the new methods that were successfully tested in this doctoral thesis, future studies should aim to identify a broad collection of functional groups. Once several groups have been

identified, one should analyze these groups to understand the interplay between their functional solutions and their biological characteristics. A simple example for such a relationship might be that a specific leg alignment causes a specific movement pattern. Importantly, research should also focus to further explore tools to select footwear constructions for functional groups that promote their health and/or performance. For example, future research should continue to investigate the relationship between comfort and footwear constructions for functional groups by further gaining an understanding about its impact on injury risk or performance. Such studies will allow to obtain conclusive evidence about whether comfort can be used to select functional beneficial footwear. In addition, it is hypothesized that understanding the unique features of a group's functional solutions will trigger the development of other approaches to select beneficial footwear for these groups.

7.6 Conclusion

A functional group is a collection of individuals with similar and group-specific functional solutions when performing a locomotion task in a specific footwear condition. This PhD research successfully developed and tested two methodological approaches that identified functional groups for running footwear. The results of this thesis showed that functional groups can be identified by (1) utilizing pattern recognition techniques, and (2) by isolating individuals who chose the same footwear as comfortable and excluding all individuals from these groups who do not share the same functional solutions. Consequently, the main outcome of this PhD research is a set of tools that can be used to identify functional groups in order to further explore them. By providing methods to enable future research about functional groups, this thesis, however, only represented a first step in attempting to utilize the concept of functional grouping in footwear biomechanics. It

is suggested that the main objective of future research about functional groups should be the development of comprehensive profiles of different functional groups. These profiles should describe each group's functional solutions, biological characteristics, and footwear requirements. It is speculated that such profiles might become highly valuable for sporting goods manufacturers in their attempt to utilize innovative manufacturing processes to establish segments of customized sports footwear.

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