TECHNISCHE
UNIVERSITÄT
WIEN
Vienna | Austria

Diploma Thesis

The Influence of Shoe Type and Performance Level on Joint Kinematics and Loading in Latin American Dancesport Specific Movements

carried out for the purpose of obtaining the degree of
Master of Science (MSc or Dipl.-Ing. or DI)
submitted at TU Wien, Faculty of Mechanical and Industrial Engineering
by

Clara Egner, BSc

Matr.Nr.: 01427745

under supervision of

Ao.Univ.Prof. Dipl.-Ing. Dr.techn. **Heinz-Bodo Schmiedmayer**

Institute of Mechanics und Mechatronics
Research Unit of Technical Dynamics and Vehicle System Dynamics
Technical University of Vienna
Getreidemarkt 9/325, 1060 Vienna, Austria

Ass.-Prof. Mag. **Hans Kainz**, MSc PhD

Department for Biomechanics, Kinesiology and Computer Science in Sport
Neuromechanics Research Group
University of Vienna
Auf der Schmelz 6a, 1150 Vienna, Austria

Vienna, January 2022

Affidavit

I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume. If text passages from sources are used literally, they are marked as such.
I confirm that this work is original and has not been submitted elsewhere for any examination, nor is it currently under consideration for a thesis elsewhere.
I acknowledge that the submitted work will be checked electronically-technically using suitable and state-of-the-art means (plagiarism detection software). On the one hand, this ensures that the submitted work was prepared according to the high-quality standards within the applicable rules to ensure good scientific practice "Code of Conduct" at the TU Wien. On the other hand, a comparison with other student theses avoids violations of my personal copyright.

Vienna, January 2022

Acknowledgements

Thank you to my supervisors, Professor Heinz-Bodo Schmiedmayer and Professor Hans Kainz. Thank you for your support, and for sharing your knowledge with me while also giving me the freedom to try things out for myself. I learned a lot writing this thesis.

Thank you to the Technical University of Vienna for being a great educational institution over the past years. Thank you to the Department for Biomechanics, Kinesiology and Computer Science in Sport at the University of Vienna for allowing me to write this thesis as part of the Neuromechanics Research Group.

Thank you to all the dancers who made this study possible by volunteering to participate.

Thank you to Willi and David, for their help with data recording and processing.

Thank you to Sebastian, for his input from a dancesport trainers perspective.

Thank you to my friends and fellow students for a lot of great teamwork and fun times during our studies.

Thank you to my parents, Angela and Ralf, and my brother Felix, for always being supportive. When I was little and asked why the sky is blue, you taught me not only that, but also why we have rainbows. Thank you for always encouraging me in my curiosity in the wonders of this world.

Kurzfassung (German Abstract)

Der Einfluss von Schuhtyp und Leistungsniveau auf die Gelenkskinematik und -belastung in Bewegungen spezifisch für Lateinamerikanischen Tanzsport

Tanzsport ist ein zunehmend beliebter Wettkampf- und Freizeitsport. Über die Biomechanik von Tanzbewegungen gibt es jedoch nur wenige Untersuchungen. Ziel dieser Studie war ein umfassender erster Überblick über die Biomechanik im Tanzstil Rumba und die Auswirkungen von Schuhwerk und Leistungsniveau darauf. Die Intention dahinter war, Erkenntnisse für die Verletzungsprävention und über die tänzerische Technik zu gewinnen.

Es wurden Marker-Trajektorien der unteren Extremitäten, Bodenreaktionskräfte und Elektromyographiedaten für den normalen Gang und verschiedene Rumba-Grundschritte gemessen. Die Daten wurden von Tänzerinnen zweier verschiedener Leistungsniveaus (Anfänger und Profis) und für drei verschiedene Absatzhöhen (barfuss, Trainingsschuhe und Lateinschuhe) erhoben. Auf der Grundlage der gemessenen Daten wurden in OpenSim muskuloskelettale Simulationen durchgeführt, um Gelenkswinkel und Kontaktkräfte in Hüft-, Knie- und Sprunggelenk zu berechnen. Der verwendete Bewegungsumfang, die mittleren Gelenkswinkel und die Gelenkskräfte wurden zwischen normalem Gang und Tanzen sowie zwischen Schuhhöhen und Leistungsniveaus verglichen. Die verwendeten Statistiken waren gepaarte t-Tests und ANOVA.

Die Ergebnisse zeigen, dass der verwendete Bewegungsumfang beim Tanzen im Vergleich zum normalen Gehen größer ist. Bei einigen Tanzbewegungen war die Spitzenkontaktkraft des Hüftgelenks höher und das Verhältnis der Kraftverteilung zwischen medialem und lateralem Kompartiment des Knies war ebenfalls höher als beim normalen Gehen. Diese Ergebnisse weisen auf mögliche Faktoren hin, die bei Tanzsportverletzungen, insbesondere bei Überlastungsschäden, eine Rolle spielen könnten.

Die Spitzenkontaktkräfte im Sprunggelenk waren in hohen Schuhen sowohl beim normalen Gehen als auch beim Tanzen geringer als barfuss. Die Absatzhöhe zeigte jedoch keine großen Auswirkungen auf die Gelenkwinkel, außer im Sprunggelenk.

Es wurden Unterschiede zwischen den Absatzhöhen und zwischen den Leistungsklassen beim Tanzen festgestellt, die jedoch nicht bei allen untersuchten Tanzbewegungen dieselben Ergebnisse zeigten. Daher ist weitere Forschung in diesem Bereich von großem Interesse, um umfangreichere und belastbarere Erkenntnisse zu gewinnen.

Zusammenfassend lässt sich sagen, dass 3D-Bewegungsanalyse in Kombination mit muskuloskelettalen Simulationen ein vielversprechendes Instrument für zukünftige Verletzungspräventionsforschung und Leistungsdiagnostik im Tanzsport darstellt.

Abstract

The Influence of Shoe Type and Performance Level on Joint Kinematics and Loading in Latin American Dancesport Specific Movements

Dancesport is an increasingly popular competitive and recreational sport. However, there is little research on biomechanics of dance movements. The goal of this study was to give a comprehensive first overview of biomechanics in Rumba dance and the effects of footwear and level of proficiency thereupon. The intention was to gain insights for injury prevention and on dance technique.
Marker trajectories of the lower extremeties, ground reaction forces and electromyography data were collected for normal gait and several basic steps of Rumba dance. Data was collected from dancers of two different performance levels (beginners and professionals) and for three different footwear heel heights (barefoot, training shoes and latin shoes). Based on measured data, musculoskeletal simulations were run in OpenSim to calculate joint angles and joint contact forces in hip, knee and ankle joint. The range of motion used, mean joint angles and joint contact forces were then compared between normal gait and dancing as well as shoe heights and levels of proficiency. Statistics used were paired t-tests and ANOVA.
The results show that the range of motion used in dancing is higher compared to normal gait. For some dance movements, peak hip joint contact force was higher and range of force distribution ratio between medial and lateral compartment of the knee was also higher compared to normal gait. These results highlight possible factors involved in dancesport injuries, especially overuse injuries.
Peak ankle joint contact forces were reduced with high-heeled shoes for both normal gait and dancing. However, heel height did not show any great effects on joint angles except in the ankle joint.
Differences between heel heights and between performance classes in dancing were found, but did not show the same results across all different dance movements analysed. Therefore, further research in the area, on a broader statistical basis, is of great interest in order to gather more reliable knowledge.
In conclusion, 3D motion analyis combined with musculoskeletal simulation was shown to be a promising tool for injury prevention research and performance diagnostics in dancesport in the future.

Contents

Acronyms

ANOVA Analysis of Variance

ASIS Anterior Superior Iliac Spine

BF Barefoot

bpm Beats per Minute

BW Body Weight

bwd Backward

chd Checked

COM Center of Mass

EMG Electromygraphy

FO Foot Off

fps Frames per Second

FS Foot Strike

fwd Forward

GRF Ground Reaction Force

GUI Graphical User Interface

ID Inverse Dynamics

IK Inverse Kinematics

IOC International Olympic Committee

JCF Joint Contact Force

JCFRR Joint Contact Force Ratio Range

l left

LF Left Foot

LS Latin Shoe

MJA Mean Joint Angle

OETSV Austrian DanceSport Federation (Ger.: Oesterreichischer Tanzsportverband)

r right

RF Right Foot

RMS Root Mean Square

ROI Region of Interest

ROM Range of Motion

SENIAM Surface Electromyography for the Non-Invasive Assessment of Muscles

SO Static Optimization

TS Training Shoe

WDSF World DanceSport Federation

xBW multiples of Body Weight

List of Figures

List of Tables

Chapter 1

Introduction and Motivation

1.1 Dancesport

Dance is, according to Merriam-Webster dictionary, defined as "an act or instance of moving one's body rhythmically usually to music: an act or instance of dancing" [1].

Dancing as a couple has been around in its social aspect for a long time. In the beginning of the 20th century, it became a competitive sport with the first competition being held in 1907. Dancesport originally refers to classical couple dances and now includes various dance styles [2]. It is an increasingly popular competitive sport, with recognition by the International Olympic Committee (IOC) since 1997 [3] and memberships of the World DanceSport Federation (WDSF) quadrupling from 1970 to 2010. Meanwhile, dancesport is also gaining popularity among amateurs and as a recreational sport [4].

In contrast to social dancing, where partners are switched often and the social aspect is paramount, dancesport athletes train with a high training frequency, fixed partnerships and the goal to maximise their performance as a couple. Factors judged in dancesport competitions include execution of specific movements, balance (static, dynamic, leading), musicality as well as interpretation and characteristic of the dance [5].

The motions in focus of this thesis are characteristic for Rumba Dance, one of the Latin dances. As defined by the WDSF: "The five Latin dances are the Samba, Cha-Cha-Cha, Rumba, Paso Doble and Jive. With their heritage in Latin American (Samba, Cha-Cha-Cha, Rumba), Hispanic (Paso Doble) and American (Jive) cultures, they each have their distinguishing traits but coincide in expressiveness, intensity and energy." [6]. Rumba was chosen because it is a dance often trained for acquiring basics also for the other dances, and because its steps are the most suited for laboratory conditions, especially the size of force plates.

1.2 Background and Motivation for Using Motion Analysis in Dancesport

1.2.1 Motion Analysis in Sports

Motion analysis has several broad fields of application, one of them lies in sports and sports science [7, 8]. Motion capture systems can be used for the means of understanding sport-specific movements better. The insights gained may help not only in improving an athlethes performance via optimisation of movements, but also aid in injury prevention [8–10].

1.2.2 Dancesport Requirements and Training

Dancesport is categorized as a technical-compositional sport with interval character [11]. Sport-scientific requirements include basic cardiovascular and muscular endurance, static and dynamic strength, speed and flexibility [11]. During competition circumstances, dancers were found to undergo high intensities indicated both by high heart rates, oxygen uptake and blood lactate levels [12].

Meanwhile, dancesport also requires athletes to meet certain standards regarding aesthetics and expression. For example an athletic-graceful physique is mentioned as preferable - not only as optimal physical prerequisite in technical aspects, but also regarding common conceptions on aesthetics in the dancesport community [13].

This is also a great factor in other dance styles with more extensive body of research, such as classical ballet. In the past, strength training has often been avoided here due to the fear of muscle hypertrophy and resulting negative impacts on aesthetics. Fortunately, this perception seems to be changing as reported by Farmer and Brouner [14]. A similar lack of awareness of the benefits of supplemental training seems to be present in the dancesport community: in a study on dancers competing at international dancesport competitions, Premelč et al. found that 72.3 % of dancers do not include any dancesport specific exercise besides dancing in their training [12].

1.2.3 Injuries in Dancesport

There is high injury potential in dancesport: As a technical sport, it is prone to overuse injuries [15]. Just in 2019, Premelč et al. found that among dancers competing at international dancesport competitions, 68.75 % reported injuries within 12 months, the most common injury sites being the neck, lower back and knee. The highest perceived cause of injury was overtraining with 25 %. However, the overall proportion of traumatic injuries was higher than the one for overuse injuries [12]. As for pain experienced by female dancers, the most common sites to experience pain are feet/ankles and again neck, lower back and knee [16].

Serveral studies on multiple dance styles have reported that supplemental training can lead to not only reduced instances of injuries, but also improve a dancers performance [14, 17–19]. Insights gained from Motion Analysis may serve as valuable input for creating dancesport-specific exercises and to prevent injuries.

Chapter 2

Research Questions

There exists little dancesport-specific biomechanical research. For this reason, the aim of this thesis was to give insight into the effects of multiple factors possibly influencing a dancers performance and health. Both kinematics and kinetics were included.
The following considerations led to the subsequent research questions being addressed:

2.1 Biomechanics of Rumba Dance

Rumba is danced to eponymous characteristic music in 4/4 time with an allowed tempo in competition of 25 to 27 bars per minute, or 100 to 108 Beats per Minute (bpm), respectively [5]. Since for most figures three steps are made per bar, this corresponds to a pace of approximately 75 to 81 steps per minute.
Rumba is a dance characterized by a delayed transfer of weight and pronounced hip movements [20, 21]. In contrast to normal human gait, steps in Rumba are not started with the heel of the foot, but the initial contact is usually made with the ball of the foot. It is followed by a weight transfer onto a flat foot while maintaining a straight leg [21, 22].
Steps during dancing and a normal gait cycle both have the basic intention of moving the body's Center of Mass (COM). However, stance flexion of the knee and the natural rolling movement in the ankle in the stance phase of normal gait can not be executed when applying Rumba technique. This means that, in order to move the COM, those movements have to be somewhat compensated in other degrees of freedom, i.e. joints, which are not evolutionarily designed to do so. In order to show which joints and degrees of freedom are responsible for creating dance movement and how this affects Joint Contact Force (JCF), normal gait and basic dance steps were compared.
The hypotheses were that higher Range of Motion (ROM) is used and higher JCF are experienced in dancing compared to normal gait. Furthermore, distribution of forces on the medial vs. lateral part of the knee was expected to be more uneven.

2.2 Shoes and their Influence on Gait - Dancing in High Heels

The footwear in latin american dance style are dance shoes with an elevated heel. A typical Latin Shoe (LS) is shown in figure 2.1, it has a heel height of around 6.5 cm and is usually worn in training and competition. Furthermore, female dancers sometimes train in shoes with a lower heel compared to the ones worn in competition, a typical Training Shoe (TS) is shown in figure 2.1. It has a heel height of around 4 cm. TS are also similar to the shoes worn by male dancers in both training and competition.

High heels alter biomechanical parameters of human gait: Hamandi and Ruken used gait analysis to find higher vertical Ground Reaction Force (GRF) and knee moment in human gait when wearing high heels [23].

Fig. 2.1: Typical latin shoe (left) and training shoe (right)

Simonsen et al. came to the same results and additionally found significantly increased Electromygraphy (EMG) parameters in high heeled gait. Indicated by their results, they hypothesize increased bone-on-bone forces in the knee joint due to the increased knee extensor moment and a correlation with the observed higher incidence of osteoarthritis in the knee joint in women compared to men [24].

High heels are known to be associated with several health conditions and increased risk of injury [25–27]. Cha found biomechanical adaptations in habituated high-heel wearers [28], and Cronin et al. found indications that long-term use of high heels may impair muscle efficiency [27]. For these reasons footwear is a possibly important factor in dance injury potential, especially for female dancers.

Some dancesport-specific research has been done regarding shoe height: Gu et al. studied lower limb muscle EMG activity during dancing in high-heeled shoes. Their results showed significantly increased EMG values in higher heels compared to flat heels for multiple muscles, indicating higher expenses for balance [29]. Li et al. investigated lower limb kinematics in Rumba square step for shoes of different heights. Their results are showing that higher heels increase maximum joint angles, likely affecting loads on lower limb joints, especially the knee. However, they did not include any considerations on kinetics [30].

Following up on these findings, data was recorded and compared for the different shoe types in order to investigate their influence on kinematics and kinetics. The hypothesis was that higher heels increase the ROM used in knee and hip joint and decrease it in ankle angle. Furthermore, higher JCF in ankle, knee and hip were expected to be found for higher heels due to the different leg position and the higher muscular activation.

2.3 Technique

Apart from the heel height, another factor of interest is the dancers experience and technique. A good technique is expected to both maximise performance and reduce injury potential. The author could not find any studies describing differences in injury potential for different performance levels. In order to investigate the matter from a biomechanical point of view, biomechanical parameters for different performance levels were compared. The hypothesis was that dancers of higher performance level use higher ROM and experience higher JCF in both knee and hip joint. Furthermore, the author hypothesized that dancers of higher performance level might show less variability when repeating movements. This is of interest regarding injury mechanisms as on the one hand, a large variability might lead to a higher chance of accidentally reaching an excessive load. On the other hand, small variability is associated with overuse injuries, such as stress fractures, due to the repetitive equal loads causing microtraumata [8].

2.4 Specific Movement Patterns Considered in this Thesis

All Figures in latin american dance consist of so-called General Actions [21]. This thesis tries to give a representative overview of the mechanics of basic General Actions. Movement patterns where the feet are closed were excluded for technical reasons (only one foot at a time should be placed on a force plate during measurement in order to ensure a unique force source).
The general actions considered in this thesis were [21]:

1. Forward (fwd) Walk
2. Checked (chd) Forward Walk
3. Checked Backward (bwd) Walk
4. Cuban Rock Actions

They were measured as parts of the following figures/movement patterns (numbers denote timing in music):

Continuous Forward Walks

2 Right Foot (RF): Forward Walk

3 Left Foot (LF): Forward Walk

Basic in Place (forward part)

41 RF: Side Walk

2 LF: Checked Forward Walk

3 RF: Weight Transfer in Place

41 LF: Side Walk

Basic in Place (backward part)

41 LF: Side Walk

2 RF: Checked Backward Walk

3 LF: Weight Transfer in Place

41 RF: Side Walk

Cuban Rocks Continuous cuban rock action while shifting the weight between the feet, maintaining the feets soles in contact with the floor.

Chapter 3

Materials and Methods

3.1 Study Design and Selection of Participants

Participants were recruited from multiple Viennese dance sport clubs. Their age range was between 23 and 31 years. In the competition system of the Austrian DanceSport Federation (Ger.: Oesterreichischer Tanzsportverband) (OETSV), dancers are divided into classes depending on their experience: D, C, B and the international classes A and S. In order to investigate the difference between beginners and top-level dancers, 8 active female dancers from D-class and 6 active female dancers from A or S class were recruited, resulting in a total of 14 participants. Data on participants is shown in table 3.1.

Class	N	Mean Age [years]	Mean Height [cm]	Mean Mass [kg]
D	8	25.0 ±2.6	166.3 ±5.5	59.9 ±4.2
A/S	6	26.6 ±1.8	162.8 ±2.4	53.7 ±3.4

Tab. 3.1: Participant characteristics (mean values per group ± one standard deviation)

3.2 Equipment and Software

3.2.1 3D Motion Capture System

All measurements were performed at the Motion Capture Lab at the Department for Biomechanics, Kinesiology and Computer Science in Sport of the University of Vienna (figure 3.1).

Fig. 3.1: Motion Capture Lab at University of Vienna

3.2.1.1 Cameras

Motion capture cameras used were Vicon Vantage V8 (Vicon Motion Systems, Oxford, UK) with a capture rate of 100 Frames per Second (fps).

3.2.2 Electromyography

EMG was recorded using a wireless multichannel electromyograph (Cometa, Bareggio, Italy). Electrodes were used along with single-use pre-gelled electrodes connected via disposable snaps (Covidien (Medtronic), Minneapolis, USA).

3.2.3 Force Plates

GRFs and moments were measured using two 3D force plates (Kistler, Vienna, Austria; Type 9281 E) with a sampling frequency of 1000 Hz.

3.2.4 Software

Software used for data recording and processing was VICON Nexus 2.11. (Vicon Motion Systems, Oxford, UK).
Further data processing and modelling was performed using Matlab R2020b (The MathWorks Inc., Natick, USA), the open-source Biomechanical ToolKit code and application Mokka 0.6.2 [31] and OpenSim 4.1 [32]. Statistical Analysis was performed using IBM SPSS Statistics 28 (IBM, New York, USA).

3.3 Experiment Design and Realisation

3.3.1 Calibration of Equipment

For each new participant, cameras were masked, the Motion Capture System was calibrated and origin was set (figure 3.2) according to *Vicon Nexus Product Guide* [33]. Before each new session, force plates were set to zero.

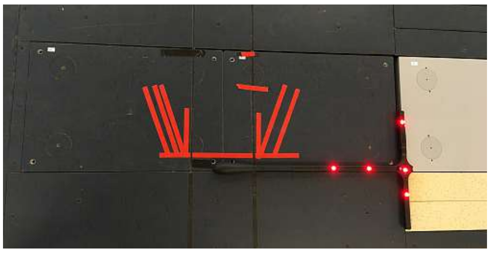

Fig. 3.2: Calibration cross placed next to force plates for origin setting

3.3.2 Marker Set and Placement

Retroreflective markers with a diameter of 14 mm were used.
The marker set used for measurements is based on the Cleveland Clinic Marker Set for the lower extremities, which shows good repeatability especially in rotation of the thigh and the shank [34]. An additional marker was added on the fifth metatarsal base in order to measure the positioning of the foot more accurately.

17 single markers and 12 markers within four trilateral clusters were used. For cluster markers, position 1 describes the superior marker of the respective cluster, 2 the inferior posterior one, and 3 the inferior anterior one. This results in a total of 29 Markers, as described in table 3.2:

Marker Label	**Placement**
Single Markers	
SACR	Sacrum (Midpoint between Left and Right Posterior Superior Iliac Spine)
LASI/RASI	Left/Right Anterior Superior Iliac Spine
LKNE/RKNE	Left/Right Lateral Condyles of the Knee
LKNM/RKNM	Left/Right Medial Condyles of the Knee
LANK/RANK	Left/Right Lateral Malleoli of the Ankle
LANM/RANM	Left/Right Medial Malleoli of the Ankle
LHEE /RHEE	Left/Right Calcaneus
LTOE /RTOE	Left/Right Second Metatarsophalangeal Joint
L5M /R5M	Left/Right Fifth Metatarsal Base
Cluster Markers	
LT1-3/RT1-3	Left/Right Thigh Cluster
LS1-3/RS1-3	Left/Right Shank Cluster

Tab. 3.2: Marker placement

Single markers were attached using double-sided adhesive tape. Cluster markers for the thigh and shank were placed on rigid, 3D-printed equilateral triangular structures with a distance between markers of 65 mm on the two long sides and 50 mm on the short side. Those were placed on the skin using double-sided tape and additionally fixed by wrapping self-adhesive sport tape. A photo of the final application is shown in figure 3.3.

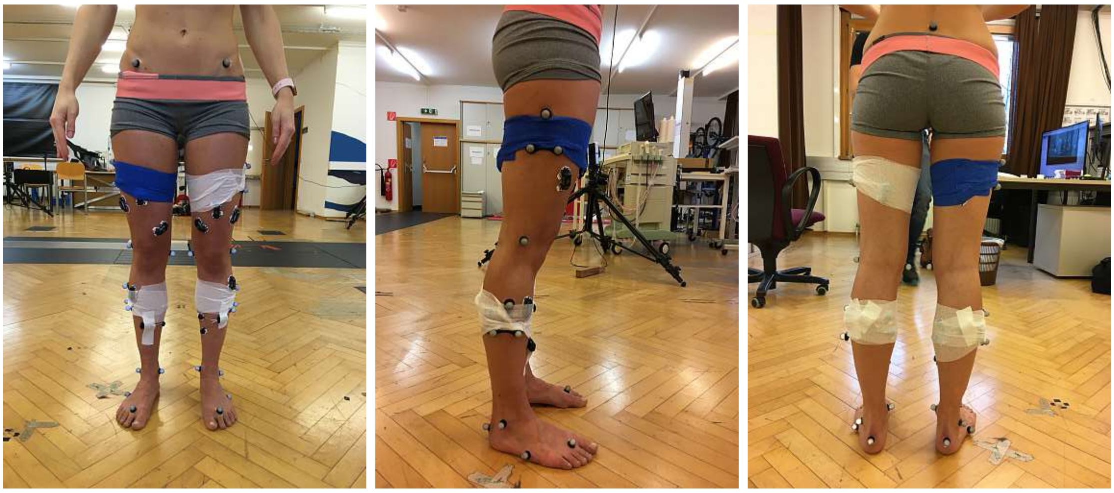

Fig. 3.3: Front-, side- and backview of markerset and electrodes applied to participant (barefoot)

3.3.3 EMG Electrode Placement

EMG electrodes were placed on shaved, clean skin, prepared using abrasive skin preparation cream (GVB-geliMED, Bad Segeberg, Germany). Placement was performed according to Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) recommendations for sensor locations on individual muscles [35]. The activities of the following muscles were recorded (table 3.3):

No.	Name	Muscle
1/2	L/R_tib_ant	Left/Right tibialis anterior
3/4	L/R_sol	Left/Right soleus
5/6	L/R_gast_lat	Left/Right gatrocnemius lateralis
7/8	L/R_gast_med	Left/Right gatrocnemius medialis
9/10	L/R_rect_fem	Left/Right rectus femoris
11/12	L/R_vast_lat	Left/Right vastus lateralis
13/14	L/R_vast_med	Left/Right vastus medialis
15/16	L/R_bic_fem	Left/Right biceps femoris

Tab. 3.3: Table of muscles for which EMG was recorded

Electrode placement can also be seen in figure 3.3.

3.3.4 Preparation and Instructions for Participants

Participants were instructed to avoid any excessive training 48 hours prior to testing in order to minimize effects of muscular exhaustion. Before the measurement, they warmed up as they normally would and were instructed to dance all movements full out. For each participant, movements were recorded in three conditions on the same day: one Barefoot (BF), one in Training Shoe (TS) and one in Latin Shoe (LS). The order of the three different conditions was selected randomly in order to avoid effects due to fatigue or habituation to the test environment. Markers on the feet were replaced when changing shoes for the next session. The remaining markers and EMG electrodes were kept as in the previous sessions to retain comparability.

3.3.5 Data Recording and Documentation

The anthropometric parameters weight, height, age and distance between left and right Anterior Superior Iliac Spine (ASIS) were measured for each participant.

An overview of the recorded movements as described in the introduction is shown in table 3.4. For each exercise and condition, at least six valid trials were recorded. Additonally, a calibration trial standing upright with one foot on each of the force plates and arms held in a T-position was recorded at the beginning of each session.

All movements except normal gait were performed to standardized timing via music of 26 bars per minute, corresponding to 104 bpm. If possible, which was the case for checked forward walk, checked backward walk and cuban rocks, multiple trials were recorded without stops in between. This was done in order to keep movements as close to the normal condition of fluent dancing as possible.

Validity of trials with regard to foot placements as well as any other exceptions, such as markers coming off and needing to be replaced, were documented. Photos of the applied markers and electrodes were taken for reference.

Exercise	**Group (2 Performance Classes)**	**Condition (3 Heel Heights)**
walk (normal gait at self-selected speed)	A/S	BF
		TS
		LS
	D	BF
		TS
		LS
forward walk	A/S	BF
		TS
		LS
	D	BF
		TS
		LS
checked forward walk	A/S	BF
		TS
		LS
	D	BF
		TS
		LS
checked backward walk	A/S	BF
		TS
		LS
	D	BF
		TS
		LS
cuban rocks	A/S	BF
		TS
		LS
	D	BF
		TS
		LS

Tab. 3.4: List of movements recorded, conditions and groups

3.4 Data Processing

3.4.1 Data Processing in Vicon

Calibration trial was labelled manually according to a custom labeling template, including the segments pelvis and left and right thigh, shank and foot. Then it was used for skeleton calibration and setting autolabel pose and skeleton parameters.

The dynamic trials were labeled automatically. If applicable, gaps were either filled automatically using the *fill gaps (Woltring)* operation in the pipeline or for larger gaps manually. Depending on the affected marker and movement, a spline, cyclic or pattern fill was used.

Marker trajectories were then filtered using a zero lag lowpass Butterworth filter with a cutoff frequency of 6 Hz.
More information on Vicon Data Processing can be found in the documentation [33].

3.4.2 Event Detection

Events were set in Mokka using the automatic event detection, which is based on vertical GRF component [36]. Threshold for the force was kept as the default of 10 N.
Events were later used for cropping trials to a Region of Interest (ROI), enabling time normalisation and consequently comparison of time course. Start and end were defined by the first Foot Strike (FS) and the last Foot Off (FO).
One exception being the cuban rocks movement, because there is no FS or FO in this movement. Instead, events were defined manually by the intercept of left and right foot vertical GRF component, hence the point at which weight is evenly distributed on both feet. Recordings were cropped and start and end were set so that one movement is going first right, then left and then right again. A visualisation of the process can be seen in the screenshot in figure 3.4.

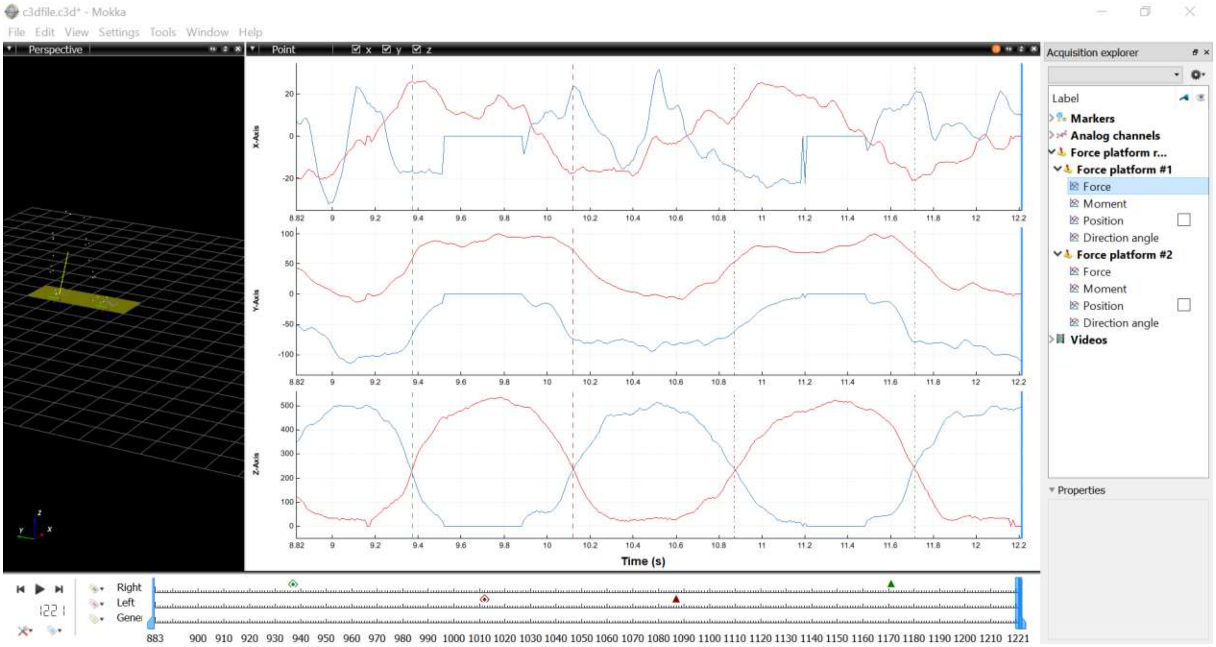

Fig. 3.4: Screenshot of event setting in Mokka: Vertical GRF [N] (labelled z-Axis) over time [s] (red (right) and blue (left) curves) and events (dotted vertical lines) for cuban rocks movement

3.4.3 Processing of c3d Files

In order to do simulations in OpenSIM, data from *.c3d* files of all caputures had to be converted to *.mot* files for GRF and *.trc* files for marker trajectories. This was done in Matlab using the utility `osimC3D.m`, especially its functions `writeMOT` and `writeTRC` [37]. Furthermore, a 4th order lowpass Butterworth filter with a cutoff frequency of 6 Hz was applied to GRF signal.

3.4.4 Musculoskeletal Models

Two different models were used in this study: Firstly, the Gait2392 model, on which detailed information can be found in the OpenSim documentation [38]. Secondly, a model developed by Lerner et al. was used for this study. It contains a detailed model of the knee joint allowing for differentiation between medial and lateral compartment of the knee [39].
To allow for larger rotations, pelvis range was set to 360 degrees for both the Gait2392 and Lerner model.

3.4.5 Scaling

In order to account for the thickness of the shoes, the markerset used for scaling was adjusted as follows: For Latin Shoe, TOE was moved 2 mm upwards and HEE 2 mm in posterior direction. For Training Shoe, TOE was moved an additional 2 mm upwards and L5M/R5M were moved 2 mm to the left/right respectively.

Scaling of the models was performed in the OpenSIM Graphical User Interface (GUI) using the calibration trial and entering the participants measured weight. Scale factors were set according to the measurements shown in tables 3.6 and 3.7, defined by the marker pairs as in table 3.5.

Measurement	**Marker Pair**	
pelvis	RASI	LASI
femur_r	RASI	RKNE
tibia_r	RKNE	RANK
foot_r	RHEE	RTOE
femur_l	LASI	LKNE
tibia_l	LKNE	LANK
foot_l	LHEE	LTOE

Tab. 3.5: Marker pairs defining measurements for scaling

Body Name	**Measurement**
pelvis	pelvis
femur_r	femur_r
tibia_r	tibia_r
talus_r	foot_r
calcn_r	foot_r
toes_r	foot_r
femur_l	femur_l
tibia_l	tibia_l
talus_l	foot_l
calcn_l	foot_l
toes_l	foot_l
torso	manually scaled according to pelvis scale factor

Tab. 3.6: Measurements used for scaling model bodies (Gait2392 model)

Body Name	**Measurement**
pelvis	pelvis
femur_r	femur_r
femoral_cond_r	femur_r
sagittal_articulation_frame_r	femur_r
med_cond_r	femur_r
lat_cond_r	femur_r
tibial_plat_r	tibia_r
tibia_r	tibia_r
patella_r	femur_r
talus_r	foot_r
calcn_r	foot_r
toes_r	foot_r
femur_l	femur_l
femoral_cond_l	femur_l
sagittal_articulation_frame_l	femur_l
med_cond_l	femur_l
lat_cond_l	femur_l
tibial_plat_l	tibia_l
tibia_l	tibia_l
patella_l	femur_l
talus_l	foot_l
calcn_l	foot_l
toes_l	foot_l
torso	manually scaled according to pelvis scale factor

Tab. 3.7: Measurements used for scaling model bodies (Lerner model)

Cluster markers were excluded for scaling. Marker weights were set to 5 for SACR, and the medial markers of the ankles and knees, and to 10 for all remaining markers. This was done since confidence in correct application was higher for those markers.
A visualisation of the standard vs. scaled model is shown in figure 3.5

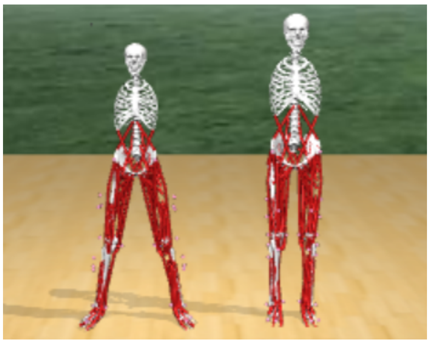

Fig. 3.5: Scaled (left) and standard (right) model

3.4.6 Strengthening of Models

All athletes participating in this study train multiple times a week and are assumed to have stronger muscles than the average population. To account for this, maximum isometric forces can be scaled, as has for example been used by Lewis et al. in the case of wheelchair athletes [40]. Since muscle forces themselves are not the main focus of this thesis, but scaling is rather used to ensure smooth muscular activation curves, a detailed determination of the ideal factor was not performed - maximum isometric forces were scaled by a factor of 2.

3.4.7 Simulations

Using the models as adjusted above and the filtered GRF as external force file, Inverse Kinematics (IK), Inverse Dynamics (ID), Static Optimization (SO) by minimizing the sum of squared muscle activations, and Joint Reaction Analysis were run in Matlab. This was done using the *Matlab OpenSIM Libraries* on which more information can be found in their documentation: [41].
Shoes weigh around 190 g for a Training Shoe (TS) and 160 g for a Latin Shoe (LS). Since those are small weights compared to Body Weight (BW), weight of the shoes was neglected in simulations.
Since IK marker errors were mostly within the OpenSIM best practice recommendations of 2–4 cm for Maximum Error, and total Root Mean Square (RMS) Error under 2 cm [42], marker weights were not further adjusted.

3.4.8 EMG Processing

EMG signals were processed as described by Bianco et al. in “Can Measured Synergy Excitations Accurately Construct Unmeasured Muscle Excitations?” [43].

3.5 Validation

For validation of simulations, several qualitative visual comparisons using data from barefoot normal gait were made: Simulated muscular activation curves were compared with the measured EMG signal. Furthermore, JCF in hip and knee were compared with the data measured with implants from the public database Orthoload [44]. For the hip, knee and ankle, JCF and joint angles were compared with the findings of Modenese et al. [45]. Medial and lateral knee JCF were compared with the findings of Holder et al. [46].

3.6 Statistical Analysis

Only data within the recommendations for marker errors as described in 3.4.7, without any simulation errors and at least three valid trials was used.
For IK and overall JCF, simulation output from the Gait 2392 model was used, since it is the more widely used model and therefore easier to compare in results. For differentiation between medial and lateral knee JCF, Lerner model was used.

Resultant JCF was calculated as the square root of the sum of squared force of each axis. IK and JCF outputs were time normalized to 0 to 100 % of stance phase, 0 % representing Foot Strike and 100 % representing Foot Off. JCF were transformed to multiples of Body Weight (xBW).

For addressing variability, the Gait Standard Deviation Measure as introduced by Sangeux et al. was used [47]. It was calculated using the 15 parameters pelvis list, pelvis tilt, pelvis rotation, and left and right hip flexion, hip adduction, hip rotation, knee angle, ankle angle and subtalar angle.

For addressing hypotheses on ROM, the average curve for all trials for one participant, movement and condition was calculated for each degree of freedom. ROM was then calculated as the maximal minus minimal value thereof, again for the respective degree of freedom (Eq. 3.1). The degrees of freedom considered were: pelvis list, pelvis tilt, pelvis rotation, and left and right hip flexion, hip adduction, hip rotation, knee angle, ankle angle and subtalar angle.

$$ROM = max(IKvalue) - min(IKvalue) \tag{3.1}$$

For addressing JCF, the average curve for all trials for one participant, movement and condition was calculated for each joint. The maximum JCF was taken as the maximum value thereof, and its position as the % of stance phase it occurred at.

For addressing distribution of medial and lateral knee JCF, ratio of lateral to total knee JCF was calculated as:

$$JCF_{ratio} = \frac{JCF_{lat}}{JCF_{lat} + JCF_{med}} \tag{3.2}$$

and the range thereof (Joint Contact Force Ratio Range (JCFRR)) as:

$$JCFRR = max(JCF_{ratio}) - min(JCF_{ratio}) \tag{3.3}$$

ROMs were compared using a mixed factorial Analysis of Variance (ANOVA), with the within-subjects factor being shoe height (condition) and the between-subjects factor being performance class (group). The same analysis was done for maximum JCF and the positions of maximum JCF.
If applicable, the Greenhouse–Geisser adjustment was used to correct for violations of sphericity. If ANOVA revealed significant results, Bonferroni-adjusted post-hoc analysis was performed in order to reveal specific within-subject or between-subjects effects.

Furthermore, differences between dancing and normal gait in ROM, maximum JCF and JCFRR were tested for using a paired-sample t-test. This was done for each condition separately and no differentiation between groups was made.

Chapter 4

Results

At multiple points in data processing, data had to be excluded due to large gaps in marker trajectories, simulation errors or marker errors exceeding limits.
For statistical analysis, only data for participants with a minimum of three valid trials was used, partially resulting in reduced sample sizes compared to the number of participants. This was especially the case for ANOVA and post-hoc analysis, since in cases of insufficient data for one condition, all data for the respective participant had to be excluded. For all the results, the sample size is given with N_{BF}, N_{TS}, N_{LS} for data analysis regarding shoe height, and $N_{A/S}$ and N_{D} for data analysis regarding performance classes, respectively.

In forward walk movement specifically, some participants had problems with their stride length being very large in relation to the distance of force plates. Due to this in addition to the previously mentioned reasons for data exclusion, statistical analysis involving ANOVA was not conducted for forward walk movement. Hence, interpretation of results of t-tests should be done with caution.

Due to the large number of statistical tests conducted and for the purpose of comprehensibility, only ANOVA results with a significant p-value ($p < .05$) and, for post-hoc regarding joint angles, results with a mean difference larger than 5° are given and discussed in this thesis. The reason thereof being that larger differences are expected to be of higher relevance in practice.
If pairwise comparison in post-hoc analysis is significant only in one group, statistics for the respective group are given. If they are significant in both groups, overall pairwise comparison results are given.
As described in the Materials and Methods (chapter 3), all given values refer to the *stance phase* of the respective step, for left (l) and/or right (r) side.

4.1 Variability

No siginifcant differences in Gait SD between shoe heights or performance classes were found.

4.2 Walk

4.2.1 Effects of Shoes and Performance Class on Inverse Kinematics

Statistics on IK for walk were performed with $N_{A/S} = 3$ and $N_D = 8$.

4.2.1.1 Results of ANOVA

Significant main effects of shoes on ROM were found as listed in table 4.1.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis list r ROM	29.802	2	14.901	5.144	.017	0.364	18
hip flexion r ROM	106.595	1.276	83.515	8.901	.009	0.497	11.487
ankle angle r ROM	96.941	2	48.470	5.936	.010	0.397	18
knee angle r ROM	184.292	1.299	141.860	16.232	.001	0.643	11.692
pelvis list l ROM	25.675	2	12.837	4.363	.029	0.326	18
hip flexion l ROM	101.895	2	50.947	5.898	.011	0.396	18
knee angle l ROM	254.572	2	127.286	16.965	<.001	0.653	18

Tab. 4.1: Significant main effects of shoes and performance class on Range of Motion in walk

Significant main effects of shoes on Mean Joint Angle (MJA) were found as listed in table 4.2.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
hip rotation r	209.498	2	104.749	20.133	<.001	0.691	18
ankle angle r	2315.858	1.288	1797.780	197.034	<.001	0.956	11.594
subtalar angle r	392.151	2	196.076	8.848	.002	0.496	
hip adduction l	16.744	2	8.372	8.454	.003	0.484	18
hip rotation l	289.887	2	144.944	17.054	<.001	0.655	18
ankle angle l	1773.629	2	886.815	148.622	<.001	0.943	18

Tab. 4.2: Significant main effects of shoes and performance class on MJA in walk

4.2.1.2 Within Subjects Effects - the Influence of Shoe Height

Bonferroni-adjusted post-hoc analysis revealed no effects on ROM with a $M_{Diff} > 5°$.

Bonferroni-adjusted post-hoc analysis revealed that MJA is by a M_{Diff} [°] > 5

- higher in outward hip rotation for LS compared to BF
  (left: $p = .003$, $M_{Diff} = 7.033$, 95%-CI[2.78, 11.286], right: $p = .002$, $M_{Diff} = 5.784$, 95%-CI[2.56, 9.007])
  and TS compared to BF
  (left: $p < .001$, $M_{Diff} = 7.084$, 95%-CI[4.012, 10.157], right: $p < .001$, $M_{Diff} = 6.196$, 95%-CI[3.428, 8.964])
  for both groups
- lower in ankle angle, hence higher plantarflexion, for LS compared to BF
  (left: $p = .003$, $M_{Diff} = 7.033$, 95%-CI[2.78, 11.286] , right: $p = .002$, $M_{Diff} = 5.784$, 95%-CI[2.56, 9.007])
  and TS compared to BF
  (left: $p < .001$, $M_{Diff} = 7.084$, 95%-CI[4.012, 10.157] , right: $p < .001$, $M_{Diff} = 6.196$, 95%-CI[3.428, 8.964])
  for both groups

- higher in right subtalar angle for TS compared to BF
  (right only: $p < .001$, $M_{\text{Diff}} = 6.196$, 95%-CI[3.428, 8.964])
  for both groups

Figure 4.1 shows joint angles over stance phase for different shoe heights.

> The results show that, when walking in elevated heels, ankle angle is, as to be expected, lower on average over the whole stance phase. Furthermore, outward hip rotation is larger over the whole stance phase compared to barefoot.
> One additional finding is that in training shoes, supination in the right foot is on average higher compared to barefoot.

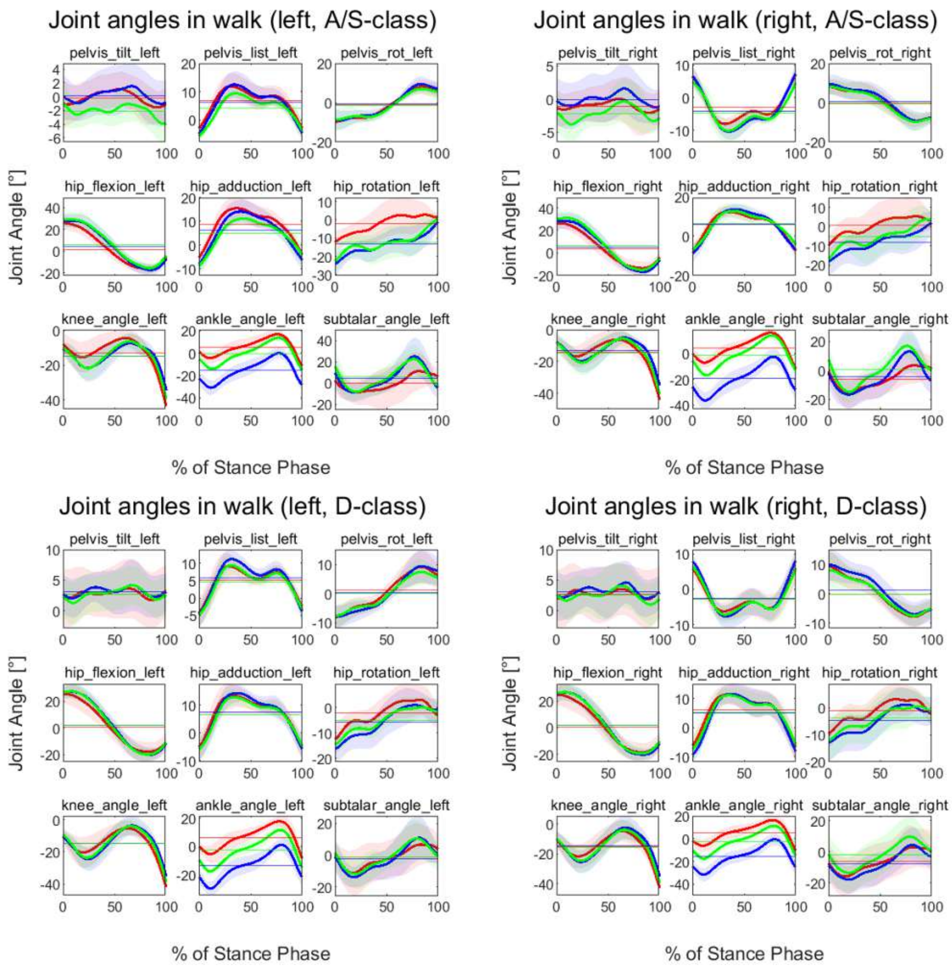

Fig. 4.1: Joint angles in the left (left) and right (right) leg over % of stance phase of walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (top) and D-class (bottom), horizontal lines denote mean values over the stace phase

4.2.1.3 Between Subjects Effects - Differences Between Performance Classes

No significant effects with a $M_{\text{Diff}} > 5°$of performance class on ROM or MJA during walk were found.

4.2.2 Effects of Shoes and Performance Class on Joint Contact Force

Statistics on JCF for walk were performed with $N_{A/S} = 3$ and $N_D = 8$.

4.2.2.1 Results of ANOVA

Significant main effects on JCF maximum and position were found as listed in table 4.3.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
ankle JCF Max r	6.428	2	3.214	17.872	<.001	0.665	18
ankle JCF Max l	6.374	2	3.187	13.055	<.001	0.592	18

Significant main effects of performance class were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
knee JCF Max l	6.845	1	6.845	5.176	.049	0.365	9

Tab. 4.3: Significant main effects of shoes and performance class on maximum Joint Contact Force and its position in walk

4.2.2.2 Within Subjects Effects - the Influence of Shoe Height

Bonferroni-adjusted post-hoc analysis revealed that maximum JCF [xBW] is

- lower in ankle the higher the heels are
  (left: LS compared to BF: p = .001, $M_{Diff} = 1.489$, 95%-CI[0.817, 2.16], TS compared to BF: p = .004, $M_{Diff} = 0.926$, 95%-CI[0.375, 1.478], LS compared to TS: p = .015, $M_{Diff} = 0.562$, 95%-CI[0.135, 0.989],
  right: LS compared to BF: p = .002, $M_{Diff} = 1.03$, 95%-CI[0.477, 1.584], TS compared to BF: p = .015, $M_{Diff} = 0.59$, 95%-CI[0.144, 1.036], LS compared to TS: p = .046, $M_{Diff} = 0.44$, 95%-CI[0.01, 0.87])
  for D-class

Figure 4.2 shows the waveforms of JCF over stance phase for different shoe heights.

Results show that when walking in elevated heels, JCF in the ankle joint is reduced the higher the heels are. This is only significant for beginners.

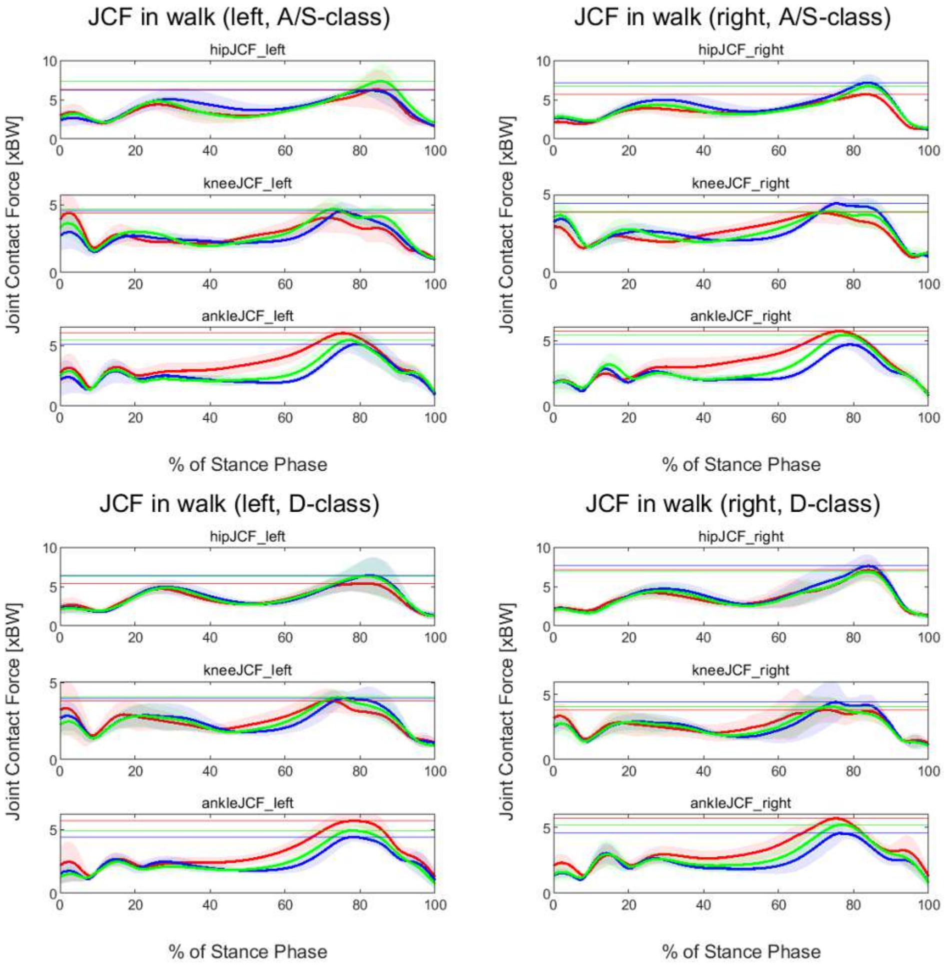

Fig. 4.2: JCF in the left (left) and right (right) leg over % of stance phase of walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (top) and D-class (bottom), horizontal lines denote max. values

4.2.2.3 Between Subjects Effects - Differences Between Performance Classes

No significant effects of performance class on JCF during walk were found.

4.3 Checked Forward Walk

4.3.1 Effects of Shoes and Performance Class on Inverse Kinematics

Statistics on IK for checked forward walk were performed with $N_{A/S} = 4$ and $N_{D} = 8$.

4.3.1.1 Results of ANOVA

Significant main effects of shoes on ROM were found as listed in table 4.4.

Significant main effects of shoes on ROM were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis tilt ROM	87.639	2	43.819	9.763	.001	0.494	20
ankle angle ROM	1916.451	2	958.226	50.864	<.001	0.836	20

Tab. 4.4: Significant main effects of shoes and performance class on Range of Motion in checked forward walk

Significant main effects of shoes and performance class on MJA were found as listed in table 4.5.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis rotation	106.229	2	53.115	7.335	.004	0.423	20
hip rotation	420.108	2	210.054	8.043	.003	0.446	20
knee angle	191.900	2	95.950	15.101	<.001	0.602	20
ankle angle	2099.095	1.125	1866.245	8.753	.011	0.467	11.248

Significant main effects of performance class were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis list	575.342	1	575.342	14.466	.003	0.591	10.000
hip rotation	1490.679	1	1490.679	20.392	.001	0.671	10.000

Tab. 4.5: Significant main effects of shoes and performance class on MJA in checked forward walk

4.3.1.2 Within Subjects Effects - the Influence of Shoe Height

Bonferroni-adjusted post-hoc analysis revealed that ROM is by a M_{Diff} [°] > 5

- lower in ankle angle the higher the heels are
  (LS compared to BF: $p < .001$, $M_{Diff} = 18.948$, 95%-CI[12.622, 25.274] , LS compared to TS: $p = .001$, $M_{Diff} = 9.955$, 95%-CI[4.31, 15.6] , TS compared to BF: $p < .001$, $M_{Diff} = 8.993$, 95%-CI[5.068, 12.919])
  for both groups

and MJA is by a M_{Diff} [°] > 5

- lower in ankle angle, hence higher plantaflexion, for LS compared to BF
  ($p < .001$, $M_{Diff} = 18.926$, 95%-CI[11.456, 26.397])
  for both groups
- higher in pelvis rotation, hence more leftward rotated, for LS compared to BF for A/S-class
  ($p = .016$, $M_{Diff} = 5.737$, 95%-CI[1.326, 10.147])

- higher in outward hip rotation for LS compared to BF
  (p = .008, M_{Diff} = 14.308, 95%-CI[4.566, 24.05])
  and TS compared to BF
  (p = .001, M_{Diff} = 13.597, 95%-CI[7.227, 19.967])
  for A/S-class

- lower in knee angle with higher heels
  (LS compared to BF: p = .003, M_{Diff} = 8.915, 95%-CI[3.935, 13.895], TS compared to BF: p = .002, M_{Diff} = 7.561, 95%-CI[3.583, 11.539])
  for A/S-class

Figure 4.3 shows joint angles over stance phase for different shoe heights.

> The results show that higher heels decrease range of motion in the ankle angle.
> Furthermore, when wearing higher heels, ankle angle is, as to be expected, lower on average over the whole stance phase.
> For experienced dancers, hip and pelvis rotation are larger and knees are more bent over the whole stance phase in high heels compared to barefoot.

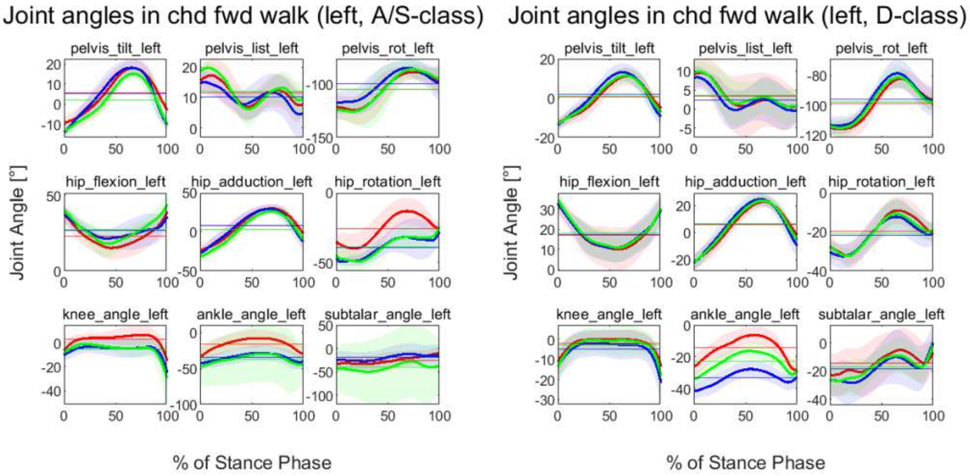

Fig. 4.3: Joint angles in the left leg over % of stance phase of checked forward walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (left) and D-class (right), horizontal lines denote mean values over the stace phase

4.3.1.3 Between Subjects Effects - Differences Between Performance Classes

Bonferroni-adjusted post-hoc analysis revealed that MJA is by a M_{Diff} [°] > 5

- higher in pelvis list, hence more tilted rightwards, for A/S-class compared to D-class
  (BF: p = .021, M_{Diff} = 8.608, 95%-CI[1.631, 15.586], TS: p = .001, M_{Diff} = 8.486, 95%-CI[4.447, 12.524], LS: p = .004, M_{Diff} = 8.347, 95%-CI[3.341, 13.354])

- higher in outward hip rotation for A/S-class compared to D-class for LS
  (p = .003, M_{Diff} = 17.768, 95%-CI[7.818, 27.718])
  and TS
  (p < .001, M_{Diff} = 17.929, 95%-CI[11.654, 24.204])

Figure 4.4 shows joint angles over stance phase for performance classes.

> Even though ROM during stance phase of checked forward walk does not differ between performance classes, the results show that hip rotation is higher on average over the whole stance phase for experienced dancers. Furthermore, with elevated heels, they keep their pelvis list higher, meaning their left hip stays higher in relation to their right hip, compared to beginners.

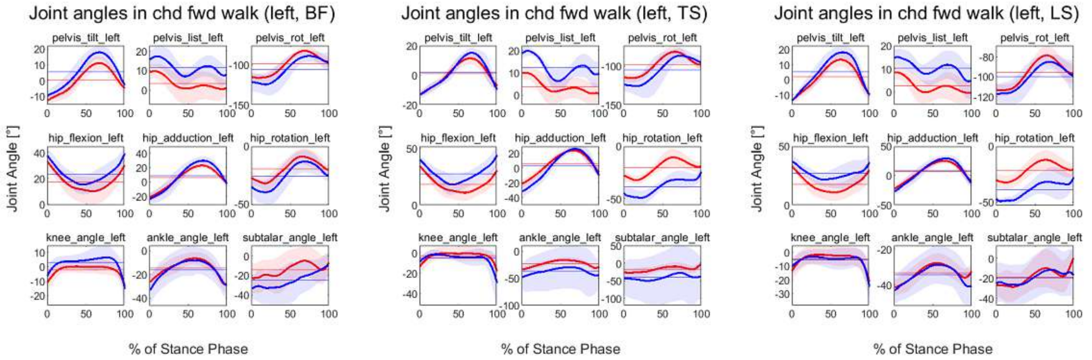

Fig. 4.4: Joint angles in the left leg over % of stance phase of checked forward walk, mean (solid line) ± one standard deviation (shadowed area) of participants from A/S-class (blue) and D-class (red) for BF (left), TS (middle) and LS (right), horizontal lines denote mean values over the stace phase

4.3.2 Effects of Shoes and Performance Class on Joint Contact Force

Statistics on JCF for checked forward walk were performed with $N_{A/S} = 4$ and $N_D = 8$.

4.3.2.1 Results of ANOVA

Significant main effects on JCF maximum and position were found as listed in table 4.6.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
ankle JCF Max	6.481	2	3.241	9.311	.001	0.482	20

Significant main effects of performance class were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
hip JCF Max	149.036	1	149.036	26.521	<.001	0.726	10.000
knee JCF Max	38.336	1	38.336	7.878	.019	0.441	10.000
hip JCF Max Position	975.347	1	975.347	6.719	.027	0.402	10.000

Tab. 4.6: Significant main effects of shoes and performance class on maximum Joint Contact Force and its position in checked forward walk

4.3.2.2 Within Subjects Effects - the Influence of Shoe Height

Bonferroni-adjusted post-hoc analysis revealed that maximum JCF [xBW] is:

- lower in ankle for LS compared to BF
  (p = .004, $M_{Diff} = 1.751$, 95%-CI[0.696, 2.807])

and TS compared to BF
($p = .01$, $M_{\text{Diff}} = 1.327$, 95%-CI[0.399, 2.256])
for A/S-class

Figure 4.5 shows the waveforms of JCF over stance phase for different shoe heights.

Results show that for experienced dancers, when wearing elevated heels JCF in the ankle joint is reduced compared to barefoot in checked forward.

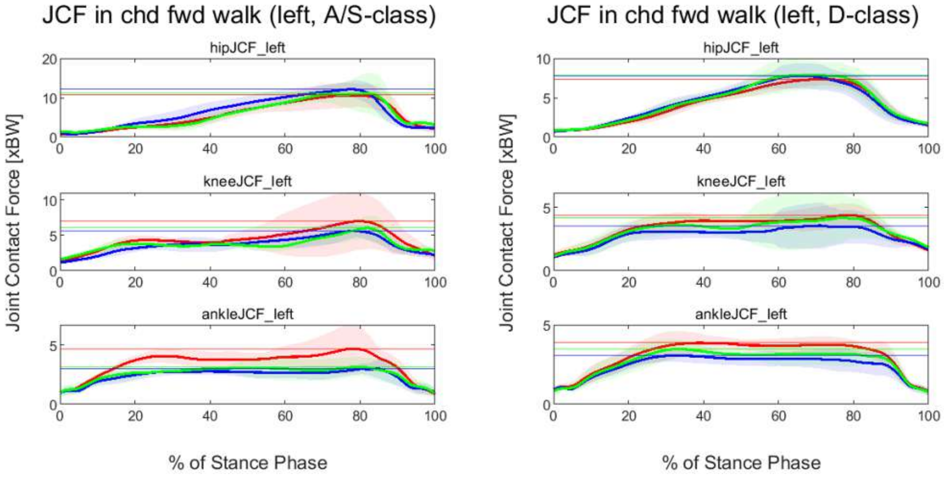

Fig. 4.5: JCF in the left leg over % of stance phase of checked forward walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (left) and D-class (right), horizontal lines denote max. values

4.3.2.3 Between Subjects Effects - Differences between Performance Classes

Bonferroni-adjusted post-hoc analysis revealed that maximum JCF [xBW] is:

- higher in hip for A/S-class compared to D-class for LS
  ($p = .002$, $M_{\text{Diff}} = 5.927$, 95%-CI[2.714, 9.14])
  and TS
  ($p = .029$, $M_{\text{Diff}} = 4.665$, 95%-CI[0.576, 8.753])
- higher in knee for A/S-class compared to D-class for LS
  ($p = .023$, $M_{\text{Diff}} = 2.682$, 95%-CI[0.455, 4.909])

Furthermore, position of maximum hip JCF is later for A/S-class compared to D-class for LS ($p = .008$, $M_{\text{Diff}} = 16.25$ [% of stance phase], 95%-CI[5.347, 27.153]) and TS ($p = .042$, $M_{\text{Diff}} = 10.5$ [% of stance phase], 95%-CI[0.492, 20.508]).

Figure 4.6 shows the waveforms of JCF over stance phase for performance classes.

Results show that in checked forward walk, experienced dancers undergo higher maximum JCF in their hip and knee joint, especially when wearing higher heels.

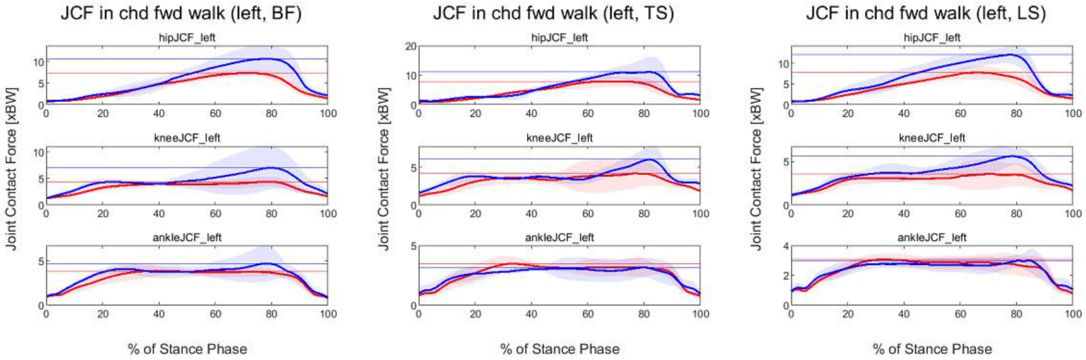

Fig. 4.6: JCF in the left leg over % of stance phase of checked forward walk, mean (solid line) ± one standard deviation (shadowed area) of participants from A/S-class (blue) and D-class (red) for BF (left), TS (middle) and LS (right), horizontal lines denote max. values

4.4 Checked Backward Walk

4.4.1 Effects of Shoes and Performance Class on Inverse Kinematics

Statistics on IK for checked backward walk were performed with $N_{A/S} = 4$ and $N_D = 7$.

4.4.1.1 Results of ANOVA

Significant main effects of shoes and performance class on ROM were found as listed in table 4.7.

Significant main effects of shoes on ROM were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis tilt ROM	99.157	2	49.578	10.401	.001	0.536	18
knee angle ROM	704.395	2	352.197	39.067	<.001	0.813	18
ankle angle ROM	606.751	2	303.376	6.866	.006	0.433	18
subtalar angle ROM	495.750	2	247.875	3.756	.043	0.294	18

Significant main effects of performance class on ROM were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
ankle angle ROM	380.629	1	380.629	12.662	.006	0.585	9
subtalar angle ROM	3181.749	1	3181.749	9.178	.014	0.505	9

Tab. 4.7: Significant main effects of shoes and performance class on Range of Motion in checked backward walk

Significant main effects of shoes on MJA were found as listed in table 4.8.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis rotation	100.130	2	50.065	14.763	<.001	0.621	18
hip rotation	309.582	2	154.791	12.107	<.001	0.574	18
ankle angle	711.378	2	355.689	3.590	.049	0.285	

Tab. 4.8: Significant main effects of shoes and performance class on MJA in checked backward walk

4.4.1.2 Within Subjects Effects - the Influence of Shoe Height

Bonferroni-adjusted post-hoc analysis revealed that ROM is by a M_{Diff} [°] > 5

- lower in knee angle for LS compared to BF
  ($p < .001$, $M_{Diff} = 11.647$, 95%-CI[8.109, 15.185]) and compared to TS
  ($p = .001$, $M_{Diff} = 7.248$, 95%-CI[3.77, 10.727])
  for both groups
- higher in subtalar angle for TS compared to LS for D-class
  ($p = .011$, $M_{Diff} = 10.393$, 95%-CI[3.033, 17.753])

and MJA is by a M_{Diff} [°] > 5

- lower in pelvis rotation, hence more rightward rotated, for LS compared to BF
  (A/S-class: $p < .001$, $M_{Diff} = 5.736$, 95%-CI[3.5, 7.971], D-class: $p = .005$, $M_{Diff} = 2.731$, 95%-CI[1.041, 4.421])

- lower in hip rotation, hence more outward rotated, for LS compared to BF
  (p = .001, M_{Diff} = 12.669, 95%-CI[6.876, 18.461])
  and TS compared to BF
  (p = .003, M_{Diff} = 10.32, 95%-CI[4.378, 16.262])
  for A/S-class
- lower in ankle angle, hence higher plantarflexion, for LS compared to TS for D-class
  (p = .018, M_{Diff} = 12.734, 95%-CI[2.794, 22.675])

Figure 4.7 shows joint angles over stance phase for different shoe heights.

Results show that in elevated heels, average ankle angle is reduced. This is only significant for beginners, presumably due to the larger sample size in this group.
Furthermore, in high heels ROM in knee angle is decreased and pelvis is on average more rightward rotated. This means that the rightward rotation, which is part of the mechanics of a checked backward walk, is more pronounced in high heels.
Additionally, average outward hip rotation is higher in elevated heels compared to barefoot for experienced dancers.
Beginners use higher ROM in subtalar angle in training shoes compared to latin shoes.

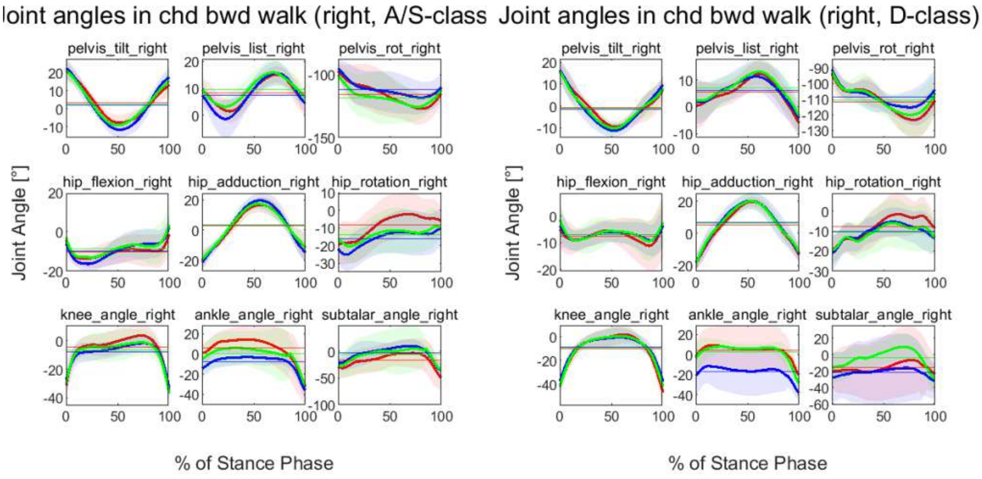

Fig. 4.7: Joint angles in the right leg over % of stance phase of checked backward walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (left) and D-class (right), horizontal lines denote mean values over the stace phase

4.4.1.3 Between Subjects Effects - Differences Between Performance Classes

Bonferroni-adjusted post-hoc analysis revealed that ROM is by a M_{Diff} [°] > 5

- higher in ankle angle for A/S-class compared to D-class for BF
  (p = .015, M_{Diff} = 14.299, 95%-CI[3.543, 25.056])
- higher in subtalar angle for A/S-class compared to D-class for LS
  (p = .001, M_{Diff} = 23.914, 95%-CI[12.986, 34.841])
  and TS
  (p = .031, M_{Diff} = 22.138, 95%-CI[2.563, 41.713])

Figure 4.8 shows joint angles over stance phase for performance classes.

Results show that experienced dancers use higher ROM in their ankle joint, depending on the shoe height either in ankle angle or subtalar angle.

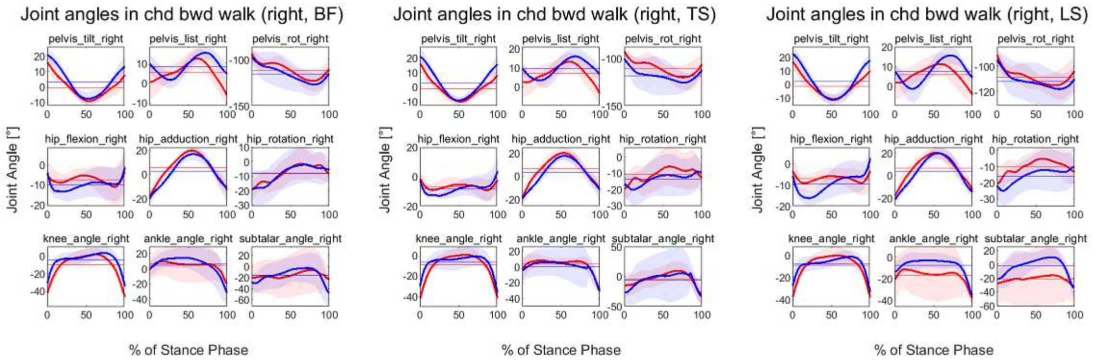

Fig. 4.8: Joint angles in the right leg over % of stance phase of checked backward, mean (solid line) ± one standard deviation (shadowed area) of participants from A/S-class (blue) and D-class (red) for BF (left), TS (middle) and LS (right), horizontal lines denote mean values over the stace phase

4.4.2 Effects of Shoes and Performance Class on Joint Contact Force

Statistics on JCF for checked backward walk were performed with $N_{A/S} = 4$ and $N_D = 7$.

4.4.2.1 Results of ANOVA

Significant main effects on JCF maximum and position were found as listed in table 4.9.

Significant main effects of shoes were found:							
Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
ankle JCF Max	1.830	2	0.915	3.575	.049	0.284	18

Significant main effects of performance class were found:							
Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
ankle JCF Max	8.884	1	8.884	8.726	.016	0.492	9.000

Tab. 4.9: Significant main effects of shoes and performance class on maximum Joint Contact Force and its position in checked backward walk

4.4.2.2 Within Subjects Effects - the Influence of Shoe Height

No significant effects of shoes on JCF during checked backward walk were found.

4.4.2.3 Between Subjects Effects - Differences Between Performance Classes

Bonferroni-adjusted post-hoc analysis revealed that maximum JCF [xBW] is:

- higher in ankle for A/S-class compared to D-class for BF
  ($p = .002$, $M_{Diff} = 1.242$, 95%-CI[0.575, 1.909])

Figure 4.9 shows the waveforms of JCF over stance phase for performance classes.

Results show that in checked forward walk, experienced dancers undego higher maximum JCF in their ankle joint than beginners when barefoot.

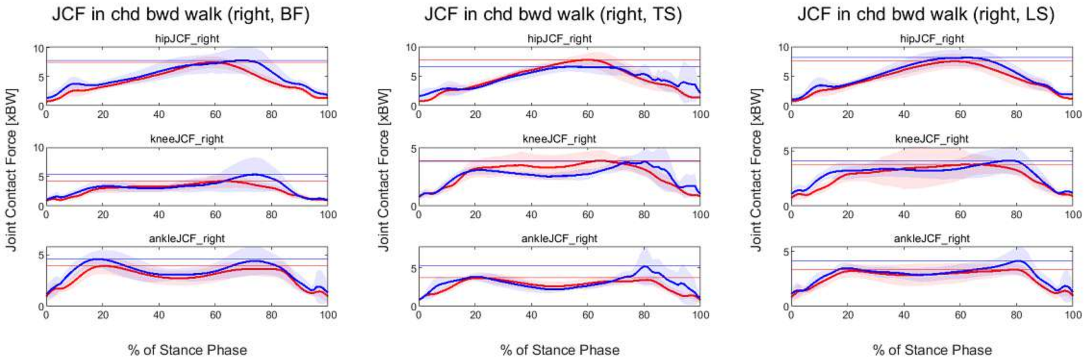

Fig. 4.9: JCF in the right leg over % of stance phase of checked backward walk, mean (solid line) ± one standard deviation (shadowed area) of participants from A/S-class (blue) and D-class (red) for BF (left), TS (middle) and LS (right), horizontal lines denote max. values

4.5 Cuban Rocks

4.5.1 Effects of Shoes and Performance Class on Inverse Kinematics

Statistics on IK for cuban rocks were performed with $N_{A/S} = 5$ and $N_D = 8$.

4.5.1.1 Results of ANOVA

Significant main effects of shoes and performance class on ROM were found as listed in table 4.10.

Significant main effects of shoes on ROM were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis rotation ROM	192.178	2	96.089	4.539	.022	0.292	22
subtalar angle ROM	1502.678	2	751.339	17.120	<.001	0.609	22
hip rotation ROM	72.478	2	36.239	4.113	.030	0.272	22
knee angle ROM	58.821	2	29.411	12.725	<.001	0.536	22

Significant main effects of performance class on ROM were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvic tilt ROM	749.613	1	749.613	6.584	.026	0.374	11
pelvis list ROM	1261.035	1	1261.035	11.466	.006	0.510	11
pelvis rotation ROM	2270.586	1	2270.586	6.559	.026	0.374	11
subtalar angle ROM	3292.984	1	3292.984	6.859	.024	0.384	11
hip adduction ROM	1979.323	1	1979.323	9.981	.009	0.476	11

Tab. 4.10: Significant main effects of shoes and performance class on Range of Motion in cuban rocks

Significant main effects of shoes on MJA were found as listed in table 4.11.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
pelvis rotation	53.922	2	26.961	8.170	.002	0.426	22
knee angle	63.806	2	31.903	8.213	.002	0.427	22
ankle angle	3421.443	1.070	3199.022	12.794	.004	0.538	22

Tab. 4.11: Significant main effects of shoes and performance class on MJA in cuban rocks

4.5.1.2 Within Subjects Effects - the Influence of Shoe Height

Bonferroni-adjusted post-hoc analysis revealed that ROM is by a M_{Diff} [°] > 5

- lower in pelvis rotation for LS compared to BF
  ($p = .002$, $M_{Diff} = 5.551$, 95%-CI[2.209, 8.893])
  for both groups

- lower in subtalar angle for LS compared to BF
  ($p = .001$, $M_{Diff} = 14.152$, 95%-CI[6.58, 21.725])
  and TS
  ($p = .001$, $M_{Diff} = 12.814$, 95%-CI[5.823, 19.805])
  for both groups

and MJA is by a M_{Diff} [°] > 5

- lower in ankle angle, hence higher plantarflexion, the higher the heels are
  (LS compared to BF: $p = .008$, $M_{Diff} = 22.189$, 95%-CI[6.038, 38.34], TS compared to BF:

p = .017, M_{Diff} = 4.186, 95%-CI[0.742, 7.63], TS compared to LS: p = .024, M_{Diff} = 18.003, 95%-CI[2.329, 33.677])
for both groups

Figure 4.10 shows joint angles over stance phase for different shoe heights.

The results show that in high heels, range of motion is decreased in pelvis rotation and subtalar angle compared to barefoot.
Furthermore, average ankle angle is lower in elevated heels, as to be expected.

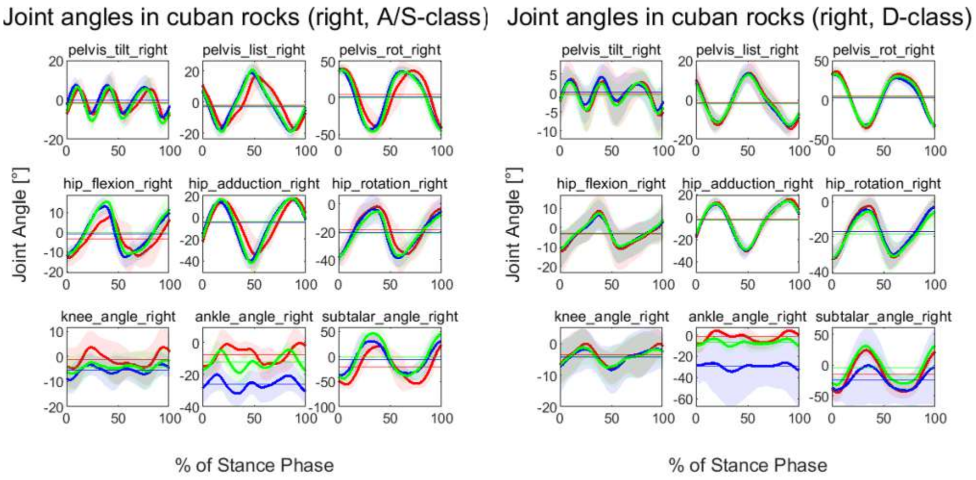

Fig. 4.10: Joint angles in the right leg over % of stance phase, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (left) and D-class (right), horizontal lines denote mean values over the stace phase

4.5.1.3 Between Subjects Effects - Differences Between Performance Classes

Bonferroni-adjusted post-hoc analysis revealed that ROM is by a M_{Diff} [°] > 5

- higher in pelvis tilt for A/S-class compared to D-class for LS
  (p = .032, M_{Diff} = 9.069, 95%-CI[0.932, 17.206])
  and TS
  (p = .016, M_{Diff} = 10.061, 95%-CI[2.32, 17.803])
- higher in pelvis list for A/S-class compared to D-class for LS
  (p = .008, M_{Diff} = 12.866, 95%-CI[4.192, 21.54]) and TS
  (p = .001, M_{Diff} = 13.982, 95%-CI[6.686, 21.278])
- higher in pelvis rotation for A/S-class compared to D-class for LS
  (p = .012, M_{Diff} = 16.588, 95%-CI[4.41, 28.766])
  and TS
  (p = .038, M_{Diff} = 17.893, 95%-CI[1.174, 34.611])
- higher in hip adduction for for A/S-class compared to D-class
  (LS: p = .016, M_{Diff} = 15.923, 95%-CI[3.619, 28.227], TS: p = .004, M_{Diff} = 17.519, 95%-CI[6.841, 28.198], BF: p = .035, M_{Diff} = 10.487, 95%-CI[0.887, 20.088])

- higher in subtalar angle for A/S-class compared to D-class for LS
  (p = .013, M_{Diff} = 26.08, 95%-CI[6.548, 45.612])

Figure 4.11 shows joint angles over stance phase for performance classes.

Results show that experienced dancers utilise higher ROM in pelvis tilt, pelvis list, pelvis rotation, hip adduction and subtalar angle than beginners, especially when wearing high heels.

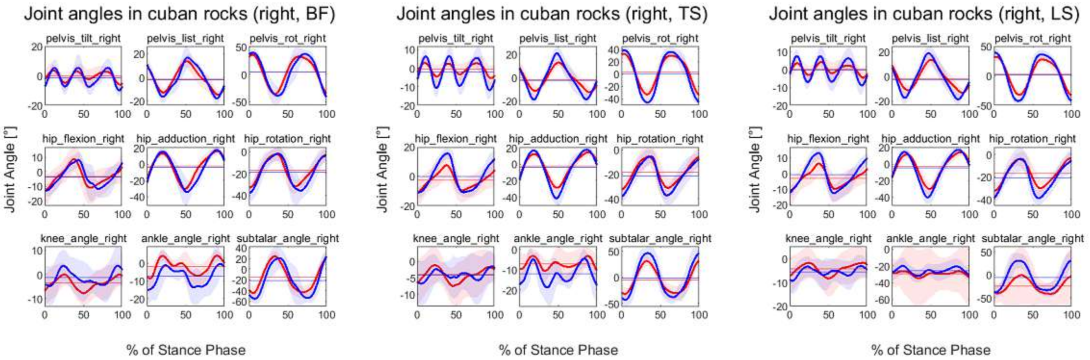

Fig. 4.11: Joint angles in the right leg over % of stance phase, mean (solid line) ± one standard deviation (shadowed area) of participants from A/S-class (blue) and D-class (red) for BF (left), TS (middle) and LS (right), horizontal lines denote mean values over the stace phase

4.5.2 Effects of Shoes and Performance Class on Joint Contact Force

Statistics on JCF for cuban rocks were performed with $N_{A/S} = 5$ and $N_D = 8$.

4.5.2.1 Results of ANOVA

Significant main effects on JCF maximum and position were found as listed in table 4.12.

Significant main effects of shoes were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
knee JCF Max	6.541	2	3.270	5.950	.009	0.351	22
ankle JCF Max	5.091	2	2.546	10.454	.001	0.487	22

Significant main effects of shoes*performance class interaction were found:

Gait Variable	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared	error df
hip JCF Max	8.375	2	4.188	5.619	.011	0.338	22.000

Tab. 4.12: Significant main effects of shoes and performance class on maximum Joint Contact Force and its position in cuban rocks

4.5.2.2 Within Subjects Effects - the Influence of Shoe Height

Bonferroni-adjusted post-hoc analysis revealed that maximum JCF [xBW] is:

- lower in knee for LS compared to BF
  (p = .007, M_{Diff} = 1.721, 95%-CI[0.59, 2.852])
  and TS compared to BF
  (p = .005, M_{Diff} = 1.85, 95%-CI[0.696, 3.004])
  for A/S-class

- lower in ankle for LS compared to BF
  ($p < .001$, $M_{\text{Diff}} = 0.906$, 95%-CI[0.463, 1.349])
  for both groups

Figure 4.12 shows the waveforms of JCF over stance phase for different shoe heights.

Results show that in elevated heels, JCF is reduced in ankle joint for both groups and additionally in knee joint for experienced dancers.

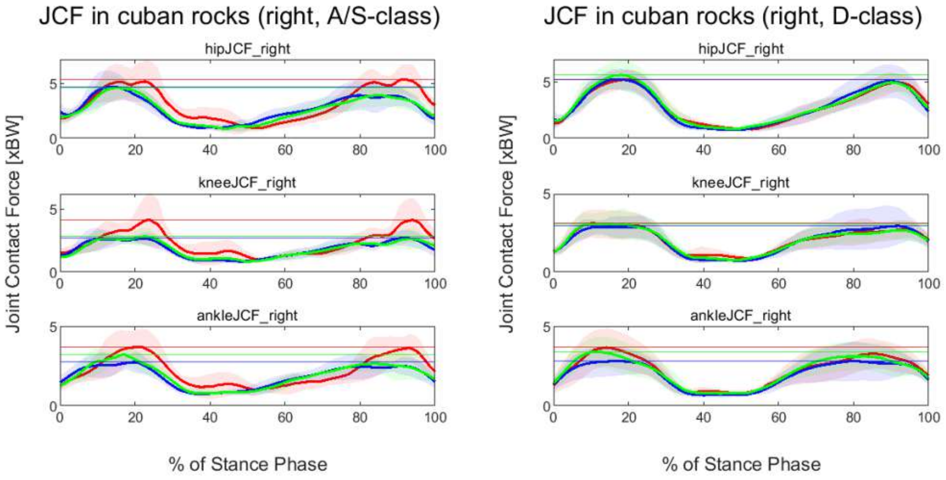

Fig. 4.12: JCF in the right leg over % of stance phase of cuban rocks, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (left) and D-class (right), horizontal lines denote max. values

4.5.2.3 Between Subjects Effects - Differences Between Performance Classes

No significant effects of performance class on JCF during cuban rocks were found.

4.6 Summary of Effects of Shoe Height and Performance Class

Summarising the results for all movements recorded and analysed, the following statements can be made:

- Ankle angle and, for checked forward walk, also ankle angle ROM, are decreased with elevated heels.
- Outward hip rotation is increased with elevated heels. This effect is more prominent for experienced dancers than for beginners.
- Overall, experienced dancers tend to use higher ROM than beginners, especially in hip and pelvis. This difference seems to be more prominent in elevated heels.
- Maximum JCF in the ankle joint is reduced with elevated heels.
- Experienced dancers tend to undergo higher maximum JCF in their hip and knee joint compared to beginners. However, reductions of maximum JCF with elevated heels seem to be more prominent in experienced dancers.

4.7 Dance Movements Compared to Walk

4.7.1 Range of Motion

4.7.1.1 Forward Walk

Statistics for forward walk were performed with $N_{BF} = 12$, $N_{TS} = 9$ and $N_{LS} = 12$.
Due to the timing in music, left and right leg are not entirely symmetrical in forward walk. The right stance phase is followed by a faster step whereas the left stance phase is followed by a deceleration, presumably resulting in differences especially in the second half of stance phase. Therefore, left and right side are not to be compared.

As listed table in 4.13, ROM is by a M_{Diff} [°] > 5
higher in forward walk than in walk for:

- pelvis tilt
- pelvis rotation
- hip flexion right (TS & LS) + left (BF)
- hip adduction right + left
- hip rotation right + left
- ankle angle right + left
- subtalar angle right + left

and lower in forward walk than in walk for:

- knee angle left

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
pelvis tilt r	BF	20.702	3.808	1.099	18.282	23.122	18.831	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	20.878	4.567	1.522	17.367	24.388	13.714	8.000	<.001	<.001	
	LS	22.075	4.729	1.365	19.070	25.079	16.170	11.000	<.001	<.001	
pelvis list r	BF	-4.093	5.114	1.476	-7.342	-0.844	-2.773	11.000	.009	.018	
	TS	-5.069	4.532	1.511	-8.552	-1.586	-3.356	8.000	.005	.010	
	LS	-6.455	6.112	1.764	-10.338	-2.571	-3.658	11.000	.002	.004	
pelvis rotation r	BF	38.631	12.178	3.515	30.894	46.369	10.989	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	40.746	10.313	3.438	32.819	48.673	11.853	8.000	<.001	<.001	
	LS	38.080	14.667	4.234	28.761	47.399	8.994	11.000	<.001	<.001	
hip flexion r	BF	11.852	7.996	2.308	6.772	16.932	5.135	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$ TS & LS
	TS	6.861	6.914	2.305	1.546	12.176	2.977	8.000	.009	.018	
	LS	5.251	7.194	2.077	0.680	9.821	2.528	11.000	.014	.028	
hip adduction r	BF	26.199	3.852	1.112	23.751	28.646	23.561	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	26.898	9.053	3.018	19.939	33.857	8.913	8.000	<.001	<.001	
	LS	24.616	8.312	2.400	19.335	29.898	10.258	11.000	<.001	<.001	
hip rotation r	BF	21.300	6.890	1.989	16.923	25.677	10.710	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	20.500	5.580	1.860	16.211	24.790	11.021	8.000	<.001	<.001	
	LS	19.376	8.363	2.414	14.063	24.690	8.026	11.000	<.001	<.001	
knee angle r	BF	3.408	5.877	1.697	-0.326	7.142	2.009	11.000	.035	.070	
	TS	3.003	5.219	1.740	-1.008	7.014	1.726	8.000	.061	.123	
	LS	0.341	5.262	1.519	-3.003	3.684	0.224	11.000	.413	.827	
ankle angle r	BF	25.149	10.504	3.032	18.475	31.823	8.294	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	15.514	8.991	2.997	8.603	22.425	5.177	8.000	<.001	.001	
	LS	9.322	7.301	2.107	4.684	13.961	4.423	11.000	.001	.001	
subtalar angle r	BF	25.846	16.349	4.720	15.458	36.233	5.476	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	32.770	14.492	4.831	21.631	43.909	6.784	8.000	<.001	<.001	
	LS	26.223	13.099	3.781	17.900	34.546	6.935	11.000	<.001	<.001	
pelvis tilt l	BF	22.261	5.536	1.598	18.744	25.779	13.929	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	23.533	4.856	1.619	19.800	27.266	14.538	8.000	<.001	<.001	
	LS	24.843	5.124	1.479	21.587	28.099	16.794	11.000	<.001	<.001	
pelvis list l	BF	-0.679	4.647	1.341	-3.632	2.274	-0.506	11.000	.311	.623	
	TS	-2.303	5.743	1.914	-6.717	2.112	-1.203	8.000	.132	.263	
	LS	-4.190	6.249	1.804	-8.161	-0.220	-2.323	11.000	.020	.040	
pelvis rotation l	BF	46.858	9.588	2.768	40.766	52.950	16.929	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	45.754	9.990	3.330	38.074	53.433	13.740	8.000	<.001	<.001	
	LS	40.523	13.347	3.853	32.043	49.003	10.517	11.000	<.001	<.001	
hip flexion l	BF	7.668	4.856	1.402	4.583	10.753	5.471	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$ TS
	TS	2.430	4.998	1.666	-1.412	6.271	1.458	8.000	.091	.183	
	LS	-0.806	3.487	1.007	-3.021	1.410	-0.800	11.000	.220	.440	
hip adduction l	BF	29.534	4.859	1.403	26.447	32.622	21.054	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	31.179	8.580	2.860	24.585	37.774	10.902	8.000	<.001	<.001	
	LS	29.995	9.360	2.702	24.048	35.941	11.101	11.000	<.001	<.001	
hip rotation l	BF	24.745	8.953	2.584	19.057	30.434	9.575	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	21.979	7.900	2.633	15.907	28.052	8.347	8.000	<.001	<.001	
	LS	17.463	8.626	2.490	11.983	22.944	7.013	11.000	<.001	<.001	
knee angle l	BF	-16.723	9.703	2.801	-22.888	-10.558	-5.970	11.000	<.001	<.001	ROM $<\text{ROM}_{\text{gait}}$
	TS	-15.971	9.413	3.138	-23.206	-8.736	-5.090	8.000	<.001	.001	
	LS	-16.280	8.140	2.350	-21.452	-11.108	-6.928	11.000	<.001	<.001	
ankle angle l	BF	23.319	8.695	2.510	17.794	28.844	9.290	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	11.663	7.824	2.608	5.649	17.677	4.472	8.000	.001	.002	
	LS	3.826	6.034	1.742	-0.008	7.659	2.196	11.000	.025	.050	
subtalar angle l	BF	21.023	12.048	3.478	13.368	28.678	6.045	11.000	<.001	<.001	ROM $>\text{ROM}_{\text{gait}}$
	TS	28.830	12.692	4.231	19.074	38.586	6.814	8.000	<.001	<.001	
	LS	19.130	13.264	3.829	10.702	27.557	4.996	11.000	<.001	<.001	

Tab. 4.13: Results of t-tests comparing ROM between forward walk and walk

4.7.1.2 Checked Forward Walk

Statistics for checked forward walk were performed with $N_{BF} = 12$, $N_{TS} = 12$ and $N_{LS} = 14$. As listed in table 4.14, ROM is by a M_{Diff} [°] > 5
higher in checked forward walk than in walk for:

- pelvis tilt
- pelvis rotation
- hip adduction left
- hip rotation left (BF & TS)
- knee angle left (BF & TS)
- subtalar angle left (BF & TS)

and lower in checked forward walk than in walk for:

- hip flexion left
- ankle angle left (TS & LS)

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
pelvis tilt	BF	21.502	6.154	1.707	17.783	25.220	12.598	12.000	<.001	<.001	ROM $>\text{ROM}_{gait}$
	TS	22.221	5.336	1.540	18.831	25.612	14.426	11.000	<.001	<.001	
	LS	25.617	6.161	1.647	22.060	29.175	15.557	13.000	<.001	<.001	
pelvis list	BF	-0.617	5.173	1.435	-3.743	2.509	-0.430	12.000	.337	.675	
	TS	-1.488	6.300	1.819	-5.491	2.515	-0.818	11.000	.215	.431	
	LS	-2.945	6.196	1.656	-6.523	0.632	-1.779	13.000	.049	.099	
pelvis rotation	BF	20.894	12.339	3.422	13.437	28.350	6.105	12.000	<.001	<.001	ROM $>\text{ROM}_{gait}$
	TS	24.231	12.638	3.648	16.201	32.261	6.642	11.000	<.001	<.001	
	LS	19.449	13.591	3.632	11.601	27.296	5.354	13.000	<.001	<.001	
hip flexion l	BF	-16.751	7.836	2.173	-21.486	-12.015	-7.707	12.000	<.001	<.001	ROM $<\text{ROM}_{gait}$
	TS	-20.442	13.139	3.793	-28.790	-12.094	-5.390	11.000	<.001	<.001	
	LS	-23.907	10.392	2.777	-29.907	-17.907	-8.608	13.000	<.001	<.001	
hip adduction l	BF	28.624	9.660	2.679	22.787	34.461	10.684	12.000	<.001	<.001	ROM $>\text{ROM}_{gait}$
	TS	29.680	9.591	2.769	23.586	35.774	10.719	11.000	<.001	<.001	
	LS	29.904	9.926	2.653	24.173	35.635	11.272	13.000	<.001	<.001	
hip rotation l	BF	9.985	8.682	2.408	4.739	15.232	4.147	12.000	.001	.001	ROM $>\text{ROM}_{gait}$ BF & TS
	TS	6.376	7.463	2.154	1.635	11.118	2.960	11.000	.006	.013	
	LS	2.864	10.222	2.732	-3.038	8.765	1.048	13.000	.157	.314	
knee angle l	BF	-20.453	5.778	1.603	-23.944	-16.961	-12.762	12.000	<.001	<.001	ROM $>\text{ROM}_{gait}$ BF & TS
	TS	-10.080	15.022	4.337	-19.625	-0.535	-2.324	11.000	.020	.040	
	LS	-7.451	10.196	2.725	-13.339	-1.564	-2.734	13.000	.009	.017	
ankle angle l	BF	1.053	8.347	2.315	-3.992	6.097	0.455	12.000	.329	.657	ROM $<\text{ROM}_{gait}$ TS & LS
	TS	-6.409	7.278	2.101	-11.034	-1.785	-3.050	11.000	.006	.011	
	LS	-14.196	5.506	1.471	-17.375	-11.017	-9.647	13.000	<.001	<.001	
subtalar angle l	BF	7.392	11.608	3.219	0.378	14.407	2.296	12.000	.020	.040	ROM $>\text{ROM}_{gait}$ BF & TS
	TS	11.102	16.383	4.729	0.693	21.512	2.348	11.000	.019	.039	
	LS	3.681	19.463	5.202	-7.557	14.918	0.708	13.000	.246	.492	

Tab. 4.14: Results of t-tests comparing ROM between checked forward walk and walk

4.7.1.3 Checked Backward Walk

Statistics for checked backward walk were performed with $N_{BF} = 12$, $N_{TS} = 11$ and $N_{LS} = 14$. As listed in table 4.15, ROM is by a M_{Diff} [°] > 5
higher in checked backward walk than in walk for:

- pelvis tilt
- pelvis rotation
- hip adduction right
- hip rotation right (BF)
- knee angle right
- ankle angle right
- subtalar angle right

and lower in checked backward walk than in walk for:

- hip flexion right

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				One-Sided p	Two-Sided p	
					Lower	Upper					
pelvis tilt	BF	23.879	7.616	2.199	19.040	28.718	10.861	11.000	<.001	<.001	ROM $>$ROM$_{gait}$
	TS	22.240	4.734	1.427	19.059	25.421	15.580	10.000	<.001	<.001	
	LS	25.950	7.214	1.928	21.785	30.115	13.460	13.000	<.001	<.001	
pelvis list	BF	3.608	7.145	2.063	-0.932	8.147	1.749	11.000	.054	.108	
	TS	2.758	7.244	2.184	-2.109	7.624	1.263	10.000	.118	.235	
	LS	1.154	8.252	2.206	-3.611	5.918	0.523	13.000	.305	.610	
pelvis rotation	BF	16.561	12.318	3.556	8.735	24.388	4.657	11.000	<.001	.001	ROM $>$ROM$_{gait}$
	TS	16.213	15.130	4.562	6.049	26.378	3.554	10.000	.003	.005	
	LS	11.792	12.872	3.440	4.361	19.224	3.428	13.000	.002	.004	
hip flexion r	BF	-26.410	6.844	1.976	-30.758	-22.061	-13.367	11.000	<.001	<.001	ROM $<$ROM$_{gait}$
	TS	-29.154	8.483	2.558	-34.853	-23.455	-11.399	10.000	<.001	<.001	
	LS	-29.274	8.786	2.348	-34.347	-24.202	-12.467	13.000	<.001	<.001	
hip adduction r	BF	18.358	10.404	3.003	11.748	24.969	6.113	11.000	<.001	<.001	ROM $>$ROM$_{gait}$
	TS	17.784	9.196	2.773	11.606	23.963	6.414	10.000	<.001	<.001	
	LS	17.630	10.810	2.889	11.389	23.871	6.102	13.000	<.001	<.001	
hip rotation r	BF	6.847	5.513	1.591	3.345	10.350	4.303	11.000	.001	.001	ROM $>$ROM$_{gait}$ BF
	TS	2.674	7.833	2.362	-2.588	7.936	1.132	10.000	.142	.284	
	LS	0.970	7.619	2.036	-3.430	5.369	0.476	13.000	.321	.642	
knee angle r	BF	10.471	9.290	2.682	4.569	16.374	3.905	11.000	.001	.002	ROM $>$ROM$_{gait}$
	TS	11.522	8.474	2.555	5.829	17.215	4.509	10.000	.001	.001	
	LS	8.015	9.517	2.544	2.520	13.510	3.151	13.000	.004	.008	
ankle angle r	BF	13.874	7.598	2.193	9.047	18.702	6.326	11.000	<.001	<.001	ROM $>$ROM$_{gait}$
	TS	10.623	5.946	1.793	6.628	14.617	5.925	10.000	<.001	<.001	
	LS	2.330	5.998	1.603	-1.133	5.793	1.453	13.000	.085	.170	
subtalar angle r	BF	20.951	15.263	4.406	11.253	30.649	4.755	11.000	<.001	.001	ROM $>$ROM$_{gait}$
	TS	23.415	17.493	5.274	11.663	35.167	4.439	10.000	.001	.001	
	LS	16.455	16.468	4.401	6.947	25.964	3.739	13.000	.001	.002	

Tab. 4.15: Results of t-tests comparing ROM between checked backward walk and walk

4.7.1.4 Cuban Rocks

Statistics for cuban rocks were performed with $N_{BF} = 13$, $N_{TS} = 12$ and $N_{LS} = 14$. As listed in table 4.16, ROM is by a M_{Diff} [°] > 5

higher in cuban rocks than in walk for:

- pelvis tilt
- pelvis list
- pelvis rotation
- hip adduction right
- hip rotation right
- subtalar angle right

and lower in cuban rocks than in walk for:

- hip flexion right
- knee angle right
- ankle angle right

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
pelvis tilt	BF	14.094	7.406	2.054	9.618	18.569	6.861	12.000	<.001	<.001	ROM $>\mathrm{ROM}_{\mathrm{gait}}$
	TS	11.403	6.577	1.899	7.225	15.582	6.006	11.000	<.001	<.001	
	LS	12.929	7.850	2.098	8.396	17.461	6.162	13.000	<.001	<.001	
pelvis list	BF	19.873	7.034	1.951	15.622	24.124	10.186	12.000	<.001	<.001	ROM $>\mathrm{ROM}_{\mathrm{gait}}$
	TS	16.864	7.786	2.248	11.917	21.812	7.503	11.000	<.001	<.001	
	LS	16.886	8.831	2.360	11.787	21.985	7.155	13.000	<.001	<.001	
pelvis rotation	BF	63.824	14.148	3.924	55.274	72.373	16.265	12.000	<.001	<.001	ROM $>\mathrm{ROM}_{\mathrm{gait}}$
	TS	59.326	16.598	4.792	48.780	69.872	12.381	11.000	<.001	<.001	
	LS	58.042	15.478	4.137	49.106	66.979	14.031	13.000	<.001	<.001	
hip flexion r	BF	-18.137	7.282	2.020	-22.537	-13.737	-8.981	12.000	<.001	<.001	ROM $<\mathrm{ROM}_{\mathrm{gait}}$
	TS	-22.718	7.380	2.131	-27.408	-18.029	-10.663	11.000	<.001	<.001	
	LS	-22.276	9.124	2.438	-27.544	-17.008	-9.135	13.000	<.001	<.001	
hip adduction r	BF	31.410	8.715	2.417	26.144	36.677	12.995	12.000	<.001	<.001	ROM $>\mathrm{ROM}_{\mathrm{gait}}$
	TS	29.286	10.570	3.051	22.570	36.001	9.598	11.000	<.001	<.001	
	LS	29.270	11.896	3.179	22.402	36.139	9.207	13.000	<.001	<.001	
hip rotation r	BF	21.123	5.605	1.554	17.736	24.509	13.588	12.000	<.001	<.001	ROM $>\mathrm{ROM}_{\mathrm{gait}}$
	TS	14.668	5.061	1.461	11.452	17.883	10.040	11.000	<.001	<.001	
	LS	16.739	8.675	2.318	11.730	21.748	7.220	13.000	<.001	<.001	
knee angle r	BF	-26.227	5.175	1.435	-29.354	-23.100	-18.274	12.000	<.001	<.001	ROM $<\mathrm{ROM}_{\mathrm{gait}}$
	TS	-25.496	3.836	1.107	-27.933	-23.059	-23.026	11.000	<.001	<.001	
	LS	-21.923	5.063	1.353	-24.846	-19.000	-16.201	13.000	<.001	<.001	
ankle angle r	BF	-9.972	6.824	1.893	-14.095	-5.848	-5.269	12.000	<.001	<.001	ROM $<\mathrm{ROM}_{\mathrm{gait}}$
	TS	-16.541	8.886	2.565	-22.187	-10.896	-6.449	11.000	<.001	<.001	
	LS	-15.042	14.962	3.999	-23.681	-6.403	-3.762	13.000	.001	.002	
subtalar angle r	BF	56.803	16.445	4.561	46.865	66.740	12.454	12.000	<.001	<.001	ROM $>\mathrm{ROM}_{\mathrm{gait}}$
	TS	50.806	20.951	6.048	37.494	64.118	8.400	11.000	<.001	<.001	
	LS	40.432	14.116	3.773	32.282	48.583	10.717	13.000	<.001	<.001	

Tab. 4.16: Results of t-tests comparing ROM between cuban rocks and walk

4.7.2 Joint Contact Forces

4.7.2.1 Forward Walk

Statistics for forward walk were performed with $N_{BF} = 12$, $N_{TS} = 9$ and $N_{LS} = 12$. As listed table in 4.17, JCF [xBW] is

higher in forward walk than in walk for:

- hip right + left
- knee right
- ankle right

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
hip JCF Max l	BF	2.274	3.128	0.903	0.286	4.261	2.518	11.000	.014	.029	$\text{JCF} > \text{JCF}_{\text{gait}}$
	TS	1.593	1.201	0.400	0.669	2.516	3.977	8.000	.002	.004	
	LS	1.995	2.492	0.719	0.412	3.578	2.774	11.000	.009	.018	
knee JCF Max l	BF	1.759	3.565	1.029	-0.506	4.023	1.709	11.000	.058	.115	
	TS	1.234	1.718	0.573	-0.086	2.555	2.156	8.000	.032	.063	
	LS	0.619	1.725	0.498	-0.477	1.715	1.244	11.000	.120	.239	
ankle JCF Max l	BF	-0.397	0.981	0.283	-1.020	0.227	-1.400	11.000	.095	.189	
	TS	0.291	1.296	0.432	-0.704	1.287	0.675	8.000	.259	.519	
	LS	0.279	1.196	0.345	-0.481	1.040	0.809	11.000	.218	.436	
hip JCF Max r	BF	2.412	2.949	0.851	0.539	4.286	2.834	11.000	.008	.016	$\text{JCF} > \text{JCF}_{\text{gait}}$
	TS	2.442	2.146	0.715	0.792	4.091	3.413	8.000	.005	.009	
	LS	2.398	2.218	0.640	0.989	3.807	3.746	11.000	.002	.003	
knee JCF Max r	BF	2.702	2.599	0.750	1.050	4.353	3.601	11.000	.002	.004	$\text{JCF} > \text{JCF}_{\text{gait}}$
	TS	2.288	2.278	0.759	0.537	4.039	3.014	8.000	.008	.017	
	LS	2.144	1.404	0.405	1.252	3.036	5.289	11.000	<.001	<.001	
ankle JCF Max r	BF	0.660	0.920	0.265	0.076	1.244	2.487	11.000	.015	.030	$\text{JCF} > \text{JCF}_{\text{gait}}$
	TS	0.755	0.507	0.169	0.365	1.145	4.465	8.000	.001	.002	
	LS	0.959	0.954	0.275	0.353	1.566	3.483	11.000	.003	.005	

Tab. 4.17: Results of t-tests comparing JCF between forward walk and walk

4.7.2.2 Checked Forward Walk

Statistics for checked forward walk were performed with $N_{BF} = 12$, $N_{TS} = 12$ and $N_{LS} = 14$. As listed in table 4.18, JCF [xBW] is

higher in checked forward walk than in walk for:

- hip left

and lower in checked forward walk than in walk for:

- ankle left

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
hip JCF Max l	BF	3.081	3.079	0.854	1.221	4.942	3.608	12.000	.002	.004	$\text{JCF} > \text{JCF}_{\text{gait}}$
	TS	2.957	2.840	0.820	1.152	4.761	3.606	11.000	.002	.004	
	LS	3.603	3.606	0.964	1.521	5.685	3.738	13.000	.001	.002	
knee JCF Max l	BF	0.932	3.483	0.966	-1.173	3.037	0.965	12.000	.177	.354	
	TS	0.703	1.780	0.514	-0.428	1.834	1.369	11.000	.099	.198	
	LS	0.822	1.502	0.401	-0.045	1.689	2.048	13.000	.031	.061	
ankle JCF Max l	BF	-1.309	2.093	0.581	-2.573	-0.044	-2.254	12.000	.022	.044	$\text{JCF} < \text{JCF}_{\text{gait}}$
	TS	-1.312	0.918	0.265	-1.895	-0.729	-4.953	11.000	<.001	<.001	
	LS	-1.452	1.249	0.334	-2.173	-0.731	-4.352	13.000	<.001	.001	

Tab. 4.18: Results of t-tests comparing JCF between checked forward walk and walk

4.7.2.3 Checked Backward Walk

Statistics for checked backward walk were performed with $N_{BF} = 12$, $N_{TS} = 11$ and $N_{LS} = 14$. As listed in table 4.19, JCF [xBW] is

lower in checked backward walk than in walk for:

- ankle

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
hip JCF Max r	BF	1.189	2.381	0.687	-0.324	2.702	1.730	11.000	.056	.112	
	TS	0.975	2.239	0.675	-0.530	2.479	1.444	10.000	.090	.179	
	LS	1.001	2.007	0.536	-0.158	2.160	1.866	13.000	.042	.085	
knee JCF Max r	BF	0.489	2.346	0.677	-1.001	1.980	0.723	11.000	.242	.485	
	TS	0.460	1.128	0.340	-0.298	1.217	1.353	10.000	.103	.206	
	LS	0.109	1.387	0.371	-0.692	0.910	0.294	13.000	.387	.774	
ankle JCF Max r	BF	-0.940	0.733	0.212	-1.406	-0.474	-4.440	11.000	<.001	.001	$\text{JCF} < \text{JCF}_{\text{gait}}$
	TS	-0.690	0.476	0.144	-1.010	-0.370	-4.807	10.000	<.001	.001	
	LS	-0.444	0.712	0.190	-0.855	-0.033	-2.332	13.000	.018	.036	

Tab. 4.19: Results of t-tests comparing JCF between checked backward walk and walk

4.7.2.4 Cuban Rocks

Statistics for cuban rocks were performed with $N_{BF} = 13$, $N_{TS} = 12$ and $N_{LS} = 14$. As listed in table 4.20, JCF [xBW] is

lower in cuban rocks than in walk for:

- hip right (TS & LS)
- knee right (TS & LS)
- ankle right

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
hip JCF Max r	BF	-0.799	2.236	0.620	-2.151	0.552	-1.289	12.000	.111	.222	JCF $<$JCF$_{\text{gait}}$ TS & LS
	TS	-1.429	1.648	0.476	-2.476	-0.382	-3.004	11.000	.006	.012	
	LS	-1.799	2.027	0.542	-2.969	-0.629	-3.322	13.000	.003	.006	
knee JCF Max r	BF	-0.640	1.865	0.517	-1.766	0.487	-1.237	12.000	.120	.240	JCF $<$JCF$_{\text{gait}}$ TS & LS
	TS	-1.005	0.927	0.268	-1.594	-0.416	-3.756	11.000	.002	.003	
	LS	-1.234	1.210	0.323	-1.932	-0.535	-3.816	13.000	.001	.002	
ankle JCF Max r	BF	-1.700	1.048	0.291	-2.333	-1.067	-5.851	12.000	$<$.001	$<$.001	JCF $<$JCF$_{\text{gait}}$
	TS	-1.604	0.607	0.175	-1.990	-1.219	-9.158	11.000	$<$.001	$<$.001	
	LS	-1.583	0.544	0.145	-1.897	-1.269	-10.890	13.000	$<$.001	$<$.001	

Tab. 4.20: Results of t-tests comparing JCF between cuban rocks and walk

4.7.3 Summary of Comparisons Between Dance Movements and Walk

Summarising the results for all movements recorded and analysed, the following statements can be made:

- In dancing, higher ROM than in normal gait is used in pelvis tilt, pelvis rotation, hip rotation and hip adduction.
- For dance movements involving a forward step, JCF in the hip are higher compared to those experienced in normal gait by approximately 1.5 to 3 xBW.
- For cuban rocks movement, which involves merely a weight shift, JCF is lower compared to normal gait in hip, knee and ankle joint by approximately 0.7 to 1.8 xBW.

4.8 Knee Joint Contact Forces Ratio Range

4.8.1 Walk (Visualisation)

Figures 4.13 and 4.14 show a visualisation of medial and lateral knee JCF and JCFRR in walk.

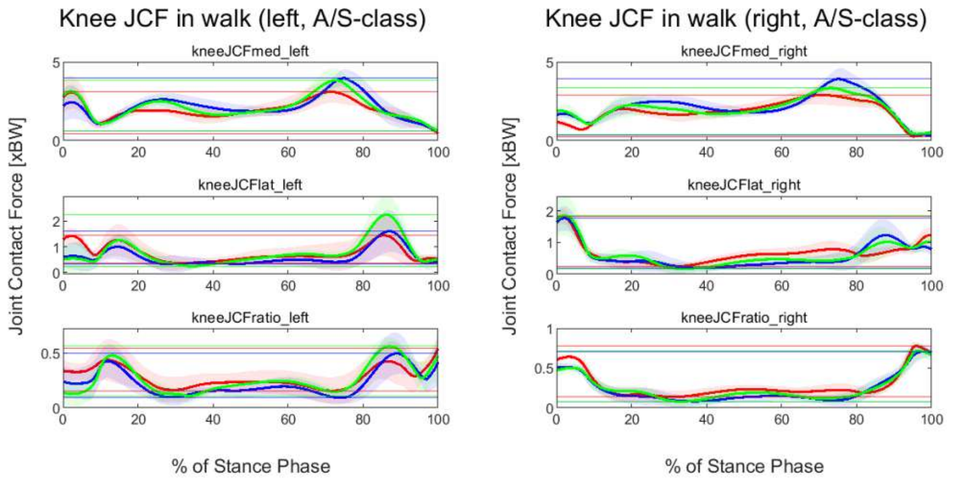

Fig. 4.13: JCF in the left (left) and right (right) leg over % of stance phase of walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class, horizontal lines denote max. and min. values

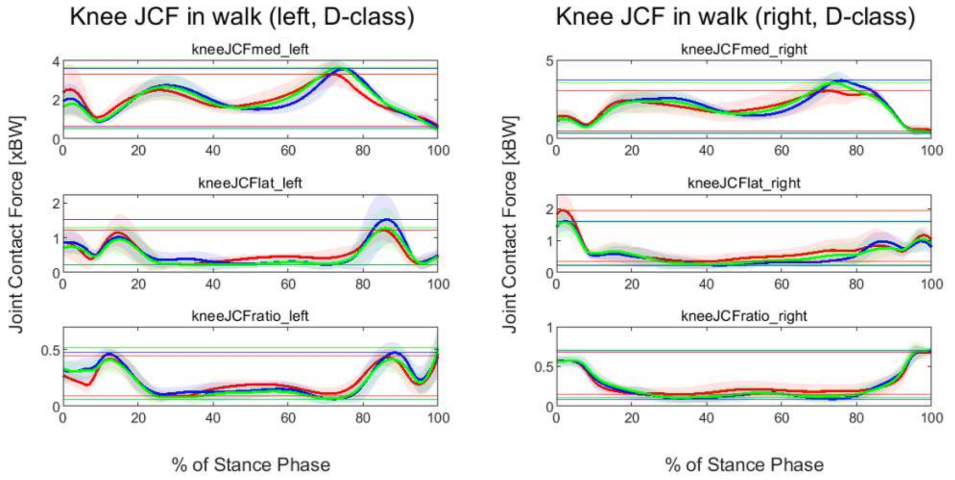

Fig. 4.14: JCF in the left (left) and right (right) leg over % of stance phase of walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for D-class, horizontal lines denote max. and min. values

4.8.2 Forward Walk

Statistics for forward walk were performed with $N_{BF} = 13$, $N_{TS} = 9$ and $N_{LS} = 12$.
As mentioned before, left and right side in forward walk are not symmetrical.
As listed in table 4.21, **JCFRR is higher in forward walk than in walk for TS in stance phase for the right leg and for BF and LS in stance phase for the left leg**.

A visualisation of medial and lateral knee JCF and JCFRR in cuban rocks is shown in figures 4.15 and 4.16.

Gait Variable	**Cond.**	**Paired Diff.**					**t**	**df**	**Significance**		**Result**
		Mean	**Std. Dev.**	**Std. Error Mean**	**95% Confidence Interval of the Difference Lower**	**Upper**			**One-Sided p**	**Two-Sided p**	
knee JCFRR l	BF	0.138	0.182	0.050	0.028	0.248	2.729	12.000	.009	.018	JCFRR >JCFRR$_{\text{gait}}$ BF & LS
	TS	0.126	0.289	0.096	-0.097	0.348	1.304	8.000	.114	.229	
	LS	0.167	0.254	0.073	0.005	0.328	2.275	11.000	.022	.044	
knee JCFRR r	BF	0.063	0.193	0.053	-0.053	0.179	1.182	12.000	.130	.260	JCFRR >JCFRR$_{\text{gait}}$ TS
	TS	0.114	0.088	0.029	0.046	0.182	3.855	8.000	.002	.005	
	LS	-0.036	0.169	0.049	-0.143	0.071	-0.737	11.000	.238	.476	

Tab. 4.21: Results of t-tests comparing knee JCFRR between forward walk and walk

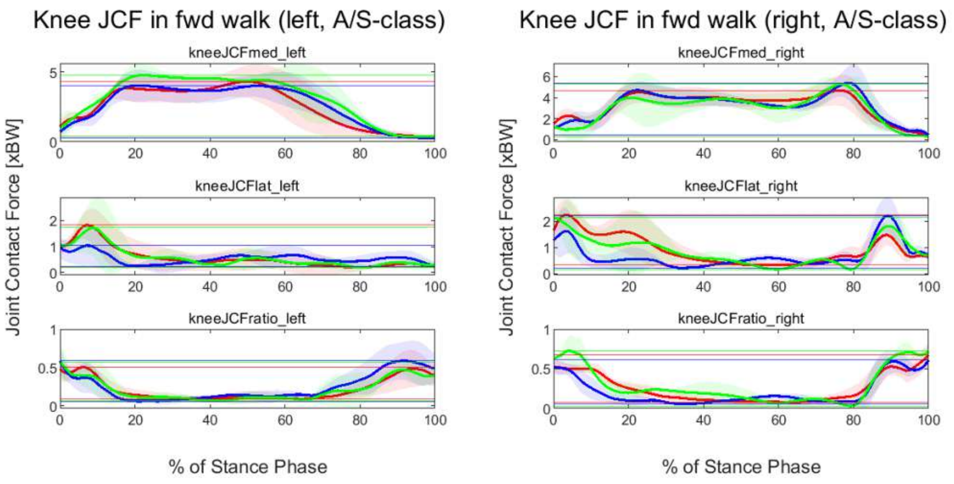

Fig. 4.15: JCF in the left (left) and right (right) leg over % of stance phase of forward walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class, horizontal lines denote max. and min. values

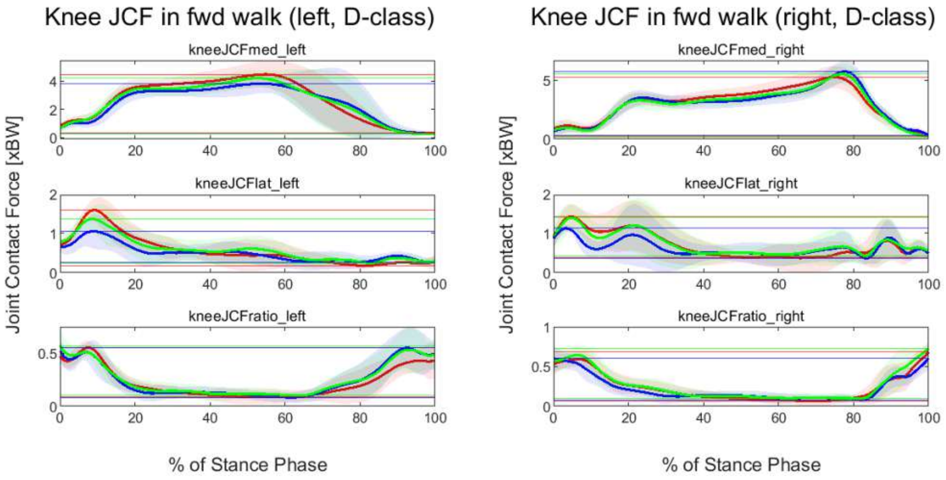

Fig. 4.16: JCF in the left (left) and right (right) leg over % of stance phase of forward walk, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for D-class, horizontal lines denote max. and min. values

4.8.3 Checked Forward Walk

Statistics for checked forward walk were performed with $N_{BF} = 14$, $N_{TS} = 12$ and $N_{LS} = 14$. As listed in table 4.22, no significant differences in JCFRR between walk and checked backward walk were found.

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
knee JCFRR l	BF	0.093	0.167	0.045	-0.004	0.190	2.077	13.000	.029	.058	
	TS	0.034	0.147	0.042	-0.060	0.127	0.794	11.000	.222	.444	
	LS	0.023	0.195	0.052	-0.090	0.136	0.444	13.000	.332	.665	

Tab. 4.22: Results of t-tests comparing knee JCFRR between checked forward walk and walk

4.8.4 Checked Backward Walk

Statistics for checked backward walk were performed with $N_{BF} = 13$, $N_{TS} = 11$ and $N_{LS} = 14$. As listed in table 4.23, **JCFRR is higher in checked backward walk than in walk for BF**.

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
knee JCFRR r	BF	0.097	0.190	0.053	-0.017	0.212	1.847	12.000	.045	.090	JCFRR >JCFRR$_{gait}$ BF
	TS	0.048	0.135	0.041	-0.043	0.139	1.167	10.000	.135	.270	
	LS	0.043	0.143	0.038	-0.040	0.125	1.113	13.000	.143	.286	

Tab. 4.23: Results of t-tests comparing knee JCFRR between checked backward walk and walk

4.8.5 Cuban Rocks

Statistics for cuban rocks were performed with $N_{BF} = 13$, $N_{TS} = 10$ and $N_{LS} = 12$. As listed in table 4.24, JCFRR is **higher in cuban rocks than in walk for all shoe heights**. A visualisation of medial and lateral knee JCF and JCFRR in cuban rocks is shown in figure 4.17.

Gait Variable	Cond.	Paired Diff.					t	df	Significance		Result
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			One-Sided p	Two-Sided p	
knee JCFRR r	BF	0.139	0.185	0.051	0.027	0.251	2.702	12.000	.010	.019	$\text{JCFRR} > \text{JCFRR}_{gait}$
	TS	0.130	0.151	0.048	0.022	0.237	2.716	9.000	.012	.024	
	LS	0.119	0.136	0.039	0.033	0.206	3.028	11.000	.006	.011	

Tab. 4.24: Results of t-tests comparing knee JCFRR between cuban rocks and walk

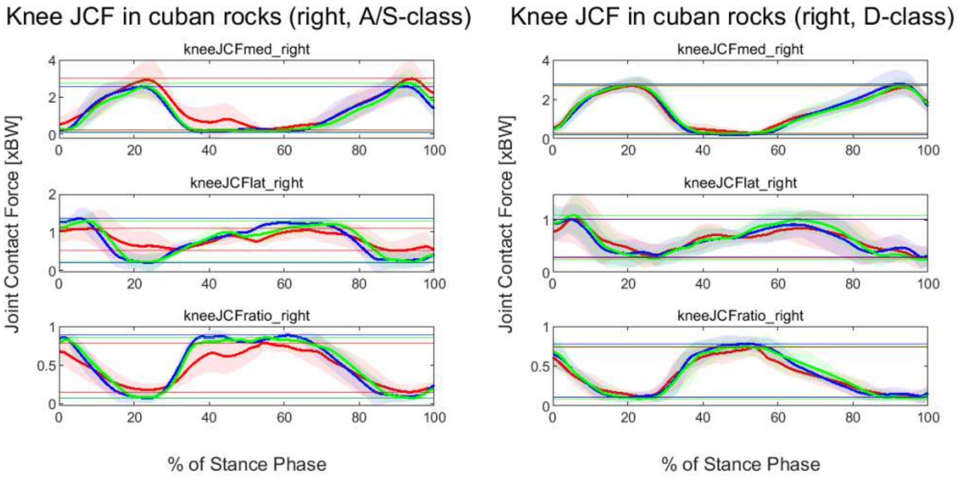

Fig. 4.17: JCF in the right leg over % of stance phase of cuban rocks, mean (solid line) ± one standard deviation (shadowed area) under conditions BF (red), TS (green) and LS (blue) for A/S-class (left) and D-class (right), horizontal lines denote max. and min. values

4.8.6 Summary of Results on JCFRR

Summarising the results for all movements recorded and analysed, it can be said that not all, but certain dance movements involve a different Joint Contact Force Ratio Range than the one experienced in normal gait. If that is the case, it is *higher* by approximately 10 to 14 %.

Chapter 5

Discussion

The results have shown certain characteristics of Rumba dance in comparison to normal human gait. Several effects of shoe heights (BF, TS and LS) and differences between performance classes (beginners: D-class and experienced dancers: A/S-class) have been found:

- The hypothesis that the Range of Motion (ROM) used in dancing is higher compared to normal human gait is supported by the results (4.7.1).
- For some dance movements, peak hip Joint Contact Force (JCF) was higher and range of force distribution ratio between medial and lateral compartment of the knee (Joint Contact Force Ratio Range (JCFRR)) was also higher compared to normal gait, as ecpected. However, the hypothesis of higher JCF in knee and ankle joint is not supported as true by the data (4.7.2, 4.8).
- Peak ankle JCF were reduced with high-heeled shoes for both normal gait and dancing. As expected, joint angles in the ankle joint were influenced by high heels. However, heel height did not show any great effects on joint angles or JCF in the knee and hip joint. Therefore, the hypotheses of increased ROM and JCF with elevated heels were contradicted by the results (4.2 - 4.5).
- Differences between heel heights and between performance classes in dancing were found, but did not show the same results across all different dance movements analysed (4.3 - 4.5).

Details on the results and possible interpretations will be discussed in the following sections.

5.1 Study Performance - Comparisons with Literature

Hip, knee and ankle JCF waveforms for barefoot normal gait can be compared with simulation data and data measured using instrumented implants. JCF waveforms qualitatively match the findings of Modenese et al. [45] (hip, knee and ankle), and Kainz et al. [48] (hip). Ankle and knee maximum JCF are also in a similar magnitude. However, the results in this thesis show higher maximum hip JCF of around 6 xBW compared to around 4 xBW in the findings of Modenese et al. [45] and around 3 xBW measured in vivo by Palmowski et al. [49]. On the other hand, Kainz et al. found similar peak hip JCF of around 6 xBW [48]. As hip JCF are strongly influenced by walking speed [50], the higher forces might have to do with a higher self-selected speed of the participants. JCF waveforms for the medial and lateral compartment of the knee joint are similar to the findings of Holder et al. [46].

5.2 Limitations

Only some results on the effects of shoe height and performance class on biomechanical parameters could be identified. This is probably due to the rather small number of participants in relation to the variability. Said variability might come from different levels of proficieny even between athletes competing within the same performance class, differences in movements depending on clubs and teachers, and personal "styles". For further research, a larger number of participants is strongly suggested.

The conditions under which exercises were performed do not fullly represent usual training or competition conditions. As already mentioned in chapter 4, for forward walk movement, some participants had problems with their stride length in relation to the distance between force plates, causing them to take their steps more carefully and shorter than they usually would. This was not the case for the remaining movements analysed. However, other factors such as the unfamiliar situation itself, the feeling of having markers and electrodes attached to their bodies, the texture of the floor in comparison to the usual wooden parquet, and, of course, the absence of a dance partner, might have altered the execution of movement.

Both of the muskuloskeletal models used only include one rotational degree-of-freedom (flexion-extension) at the knee joint. Since all analyses refer to the stance phase of the respective step, where knees are mostly kept straight and therefore are not able to rotate as much anyhow, the resulting error can be assumed as neglegible.
Furthermore, effects of the shoe soles material and shoe geometry, which could alter dynamics of movement, were not taken into account in simulations.

Dancing consists of sequences of a vairety of different movements. Even though the movements analysed in this thesis are very common ones, their exact mechanics are likely to vary depending on the preceeding and following steps. The results give a general idea on the scale of biomechanical parameters in dancing. However, they are probably not representative of the full spectrum of what is experienced by a dancers body over the whole dance routine.
Participants of this study are female dancers who mostly dance in the role of the follower. It is not certain that the results will be the same as for dancers of other sexes and/or dancers that are used to dancing the leading part.

5.3 Comparison of Dance Movements with Normal Gait

For all dance steps analyzed, ROM during stance phase was shown to be higher than in normal gait for pelvis tilt, pelvis rotation, hip rotation and hip adduction. This reflects the characteristic movements for Rumba dance as described in 2.1.

Hip JCF were shown to be higher than in walk for dance steps directed forward. Within the context of the increased ROM in the hip and pelvis, the suggestions are reasonable that increased hip JCF could be due to higher muscular activations in that area or different moment arms/distance to the ground reaction force.

5.4 Effects of Shoe Height in Normal Gait

For normal gait, outward hip rotation and plantarflexion were found to be higher with elevated heels.
The increased plantarflexion is directly expained by the elevated heel and has also been found in other studies on high-heeled gait, for example by Snow and Williams [51]. Additionally, they found less foot abduction, larger supination at heel strike, but no significant differences

in pelvic tilt or average lumbar curvature with high heels [51]. Other studies investigating gait kinematics in high heels were focused mainly on parameters regarding pelvis and came to different conclusions: Mika et al. found an increase in pelvic range of motion in the sagittal plane during high-heeled gait for women between 20 to 25 years of age [52]. Schroeder and Hollander found a reduced pelvic tilt and increased transversal pelvic rotation in high-heeled standing and walking [53].

Since an increased outward hip rotation has not been found by any of the studies cited above, it is likely that this finding is rather related to the participants being dancers than to the heel height itself. Dancers are used to wearing Training Shoes (TS) and Latin Shoes (LS) when dancing. It is probable that they therefore adopt a certain posture when wearing those shoes, even when they are not dancing but only walking. One part of the standard posture in latin dance is a slight "V-shape" in the legs and feet, which could explain the outward hip rotation. Consequently, this effect of shoe height on biomechanical parameters in normal gait may not be generalisable or comparable to the average population.

Similarly, the fact that no significant differences in pelvic kinematic parameters were found in this study could be because of the stabilising muscles in a dancers posture.

Maximum JCF in the ankle joint was shown to be reduced the higher the heels are. When looking at figure 4.1, one can see that the peak is reached at the end of stance phase, hence during a push off phase. This means the plantarflexor muscles are working at that moment. The maximum isometric force of ankle plantar flexors is shown to be in dorsiflexed position (around 20° of dorsiflexion) [54, 55], hence for a lengthened muscle. Therefore, one reason for the reduced JCF could be that lower muscle forces may be acting due to the ankle angles reached when heels are elevated.

5.5 Effects of Shoe Height and Performance Class in Dance Movements

As in normal gait, outward hip rotation and platarflexion were found to be higher with elevated heels. Results again revealed that maximum ankle JCF are often reduced in TS and especially LS. When looking at the figures, one can observe that the maxima of ankle JCF are mostly reached either when weight is transferred onto the foot or during a push off phase. Since steps are made with the ball of the foot first, plantar- and dorsiflexors are working in both cases. Therefore, these results are explainable again as described above (5.4). For some movements, ankle angle ROM is additionally decreased with elevated heels compared to barefoot.

The other findings for dance movements are not as straighforward and leave room for speculation: For cuban rock movement, ROM was shown to be limited by elevated heels. The findings of Li et al., who showed an increased ROM used in Rumba square step with elevated heels compared to flat feet [30], could not be supported hereby.

Shoe height has not been shown to have an effect on the JCF in hip and knee joints.

Overall, experienced dancers tend to use higher ROM or have mean joint angles further away from the anatomical pose than beginners, especially in hip and pelvis. Interestingly, this difference trends to be more prominent in elevated heels. This indicates that even though higher heels have not been shown to have a significant influence on ROM in hip and pelvis, experienced dancers may be able to use their higher ROM even in high heels whereas beginners might be more limited by them.

For those movements, where differences in JCF between performance classes were found, it was the case that experienced dancers undergo higher JCF in the respective joint than beginners. Since the results also revealed that experienced dancers use a higher ROM, it is again probable that the higher forces acting on the joints are due to muscular activation for positioning and/or stabilisation, rather than gravitational ones.

The hypothesis of less variability in repeating movements for professionals has not shown to be accurate. This means that a higher risk for overuse injuries in dancers of high performance level is not to be expected based on this study.

5.6 Knee Joint Contact Force Ratio Range

As described in 4.8.6, in some movements dancers undergo higher knee JCFRR than in normal gait. An increase in JCFRR means that the peak proportion of lateral force and/or medial force increases. Similarly to the peaks of ankle JCF, the peaks of lateral compartment knee JCF seem to occur when weight is transferred onto the foot or during a push off phase, whereas medial compartment knee JCF are highest during the stance phase. This can be seen in the figures in section 4.8.

When looking at figure 4.17, which shows knee JCFRR in cuban rocks, especially the peaks of the lateral knee JCF seem to be increased compared to normal gait (shown in figure 4.13 and 4.14). Cuban rocks are a movement where the weight is partly shifted between left an right while the hips are moving in a "figure 8" in the transversal plane [22]. As this movement has a large sideward component, which normal gait does not, the increased proportion of lateral knee JCF is comprehensible. Such sideward movements are repetitively done in Rumba dance [21, 22].

Furthermore, a similar result has been found for some shoe heights also for forward walks. This result indicates that due to the specific mechanics of forward walks in Rumba dance, the force distribution in the knee shows similarities to that in a *sideward* movement. This may likely be because of the rotative movement of the hips characteristic for Rumba dance.

Increased forces in one compartment of the knee due to varus/valgus malalignments have been associated with knee osteoarthritis in the respective compartment [46, 56, 57]. If an athlete already has a malalignment and additionally undergoes large JCFRR when dancing, the combination of factors might lead to high loads in one compartment of the knee. Based on these findings, varus/valgus malalignments in dancesport athletes should be closely monitored by teachers and physiotherapists. Further research on relashionships between knee injuries and lower limb alignment in dancers is of great interest for injury prevention.

5.7 Lateralities

There were results only significant for right side: e.g. subtalar MJA is higher for TS than BF only on the right side in walk. Most figures in dancesport are not symmetric. Dancers may tend to execute certain movements predominantly on one side and consequently have imbalances. Strength imbalances have already been found specifically for Latin Formation dancers by Wanke et al. [58]. Another reason could be that it is not muscular imbalances but simply a habituation to moving differently on left and right side causing the difference.

5.8 Conclusion and Outlook

Overall, the results of the study indicate that the effects of heel height are limited to the ankle joint and do not extend to knee and hip joint. Therefore, injuries in the hip and knee joint are probably related to other factors.

Since differences between performance classes can be shown using motion analysis, it might serve as a helpful tool to further examine dance technique and what makes a good dancer for other dance steps and dances.

Some possible factors in injury prevention have been identified. Further research on the topic is of great interest and may include:

- Studies including all sexes and different age groups, as dancesport athletes are active in different age classes starting from 9 years of age and without any upper limitation [5].
- Studies with a larger number of participants and on relationships between biomechanical parameters and previous injuries in dancesport athletes.
- Further exploration of EMG data, in order to find which muscles are active in order to execute dance movements, muscle synergies and possible co-contractions.
- Possible compensatory movements in the upper body.

A comprehensive overview of the potentials of motion analysis in dancesport has been given on the example of Rumba dance. Based on the results, it can be concluded that 3D motion analyis combined with musculoskeletal simulation is a promising tool for performance diagnostics and injury prevention in dancesport in the future.

For dancers may keep on practising their sport successfully and in a healthy way for a long time.

Bibliography

[1] M.-W. Dictionary. *Dance*. 2020. URL: `https://www.merriam-webster.com/dictionary/dance` (visited on 12/09/2020).

[2] WDSF. *World Dancesprt Federation: About Dancesport*. 2010-2020. URL: `http://www.worlddancesport.org/About` (visited on 12/09/2020).

[3] WDSF. *World Dancesprt Federation: History*. 2010-2020. URL: `https://www.worlddancesport.org/WDSF/History` (visited on 01/13/2021).

[4] WDSF. *World Dancesprt Federation: Members*. 2010-2020. URL: `https://www.worlddancesport.org/WDSF/Membership` (visited on 01/13/2021).

[5] WDSF. *World Dancesprt Federation: Competition Rules*. 2010-2020. URL: `https://www.worlddancesport.org/Rule/Athlete/Competition` (visited on 12/09/2020).

[6] WDSF. *World Dancesprt Federation: Disciplines*. 2010-2020. URL: `http://www.worlddancesport.org/About/Dance_Styles/DanceSport_Disciplines` (visited on 12/09/2020).

[7] E. van der Kruk and M. M. Reijne. "Accuracy of human motion capture systems for sport applications; state-of-the-art review". eng. In: 18.6 (2018), pp. 806–819. ISSN: 1746-1391.

[8] N. Stergiou. *Biomechanics and Gait Analysis*. eng. San Diego: Elsevier Science and Technology, 2020. ISBN: 0128133724.

[9] M. Wilson and Y.-H. Kwon. "The role of biomechanics in understanding dance movement: a review". In: *Journal of Dance Medicine and Science* 12 (2008), p. 109.

[10] Y. Koutedakis, E. O. Owolabi, and M. Apostolos. "Dance biomechanics: a tool for controlling health, fitness, and training". In: *Journal of Dance Medicine and Science* 12 (2008), p. 83.

[11] N. Thierse, R. Grüninger, and M. Schmalzbauer. *Tanzsportmedizin*. Ed. by E. M. Wanke. Sportverlag Strauss, 2011, pp. 54–59. ISBN: 978-3-86884-002-5.

[12] J. Premelč, G. Vučković, N. James, and L. Dimitriou. "A Retrospective Investigation on Age and Gender Differences of Injuries in DanceSport". In: *Int. J. Environ. Res. Public Health* 16 (2019), p. 4164.

[13] E. M. Wanke. *Tanzsportmedizin*. Ed. by E. M. Wanke. Sportverlag Strauss, 2011, p. 65. ISBN: 978-3-86884-002-5.

[14] C. Farmer and J. Brouner. "Perceptions of Strength Training in Dance". In: *Journal of Dance Medicine & Science* 25.3 (Sept. 15, 2021), pp. 160–168. ISSN: 1089-313X. DOI: `doi:10.12678/1089-313X.091521a`. URL: `https://www.ingentaconnect.com/content/jmrp/jdms/2021/00000025/00000003/art00001`.

[15] R. Bahr. *The IOC manual of sports injuries : an illustrated guide to the management of injuries in physical activity*. eng. Chichester, West Sussex, UK: Wiley-Blackwell, 2012. ISBN: 1280713976.

[16] D. Miletic, A. Miletic, I. K. Lujan, A. Kezic, and M. Erceg. "Health Care Related Problems Among Female Sport Dancers". In: *International Journal of Athletic Therapy and Training* 20.1 (2015), pp. 57–62. URL: `https://journals.humankinetics.com/view/journals/ijatt/20/1/article-p57.xml`.

[17] Y. Koutedakis, A. Stavropoulos-Kalinoglou, and G. Metsios. “The Significance of Muscular Strength in Dance”. In: *Journal of Dance Medicine & Science* 9.1 (Mar. 1, 2005), pp. 29–34. ISSN: 1089-313X. URL: `ttps://www.ingentaconnect.com/content/jmrp/jdms/2005/00000009/00000001/art00006`.

[18] Y. Koutedakis and N. C. C. Sharp. “Thigh-muscles strength training, dance exercise, dynamometry, and anthropometry in professional ballerinas”. In: *Journal of strength and conditioning research* 18.4 (Nov. 2004), pp. 714–718. ISSN: 1064-8011. DOI: `10.1519/13983.1`. URL: `https://doi.org/10.1519/13983.1`.

[19] J. Russell. “Preventing dance injuries: current perspectives”. In: *Open Access J Sports Med* 4 (2013), pp. 199–210. DOI: `doi:10.2147/OAJSM.S36529`.

[20] M.-W. Dictionary. *Rumba*. 2020. URL: `https://www.merriam-webster.com/dictionary/rumba` (visited on 02/03/2021).

[21] Sietas, Ambroz, Cacciari, Cacciari, Bosco, Ferrari, and Cavallini. *Rumba*. 1st ed. Rome: Grafiche BIME, 2013.

[22] W. Laird. *Technique of Latin Dancing*. International Dance Teachers’ Association Ltd, 1988. ISBN: 090032621.

[23] S. J. Hamandi and D. M. Ruken. “Biomechanical study with kinematic and kinetic descriptions of the effect of high-heeled shoes in healthy adult females based on gait analysis”. eng. In: *IOP conference series. Materials Science and Engineering* 671.1 (2020), p. 12063. ISSN: 1757-8981.

[24] E. B. Simonsen, M. B. Svendsen, A. Nørreslet, H. K. Baldvinsson, T. Heilskov-Hansen, P. K. Larsen, T. Alkjær, and M. Henriksen. “Walking on high heels changes muscle activity and the dynamics of human walking significantly”. eng. In: *Journal of applied biomechanics* 28.1 (2012), pp. 20–28. ISSN: 1065-8483.

[25] J. X. Moore, B. Lambert, G. P. Jenkins, and G. McGwin. “Epidemiology of High-Heel Shoe Injuries in U.S. Women: 2002 to 2012”. eng. In: *The Journal of foot and ankle surgery* 54.4 (2015), pp. 615–619. ISSN: 1067-2516.

[26] N. J. Cronin. “The effects of high heeled shoes on female gait: A review”. eng. In: *Journal of electromyography and kinesiology* 24.2 (2014), pp. 258–263. ISSN: 1050-6411.

[27] N. J. Cronin, R. S. Barrett, and C. P. Carty. “Long-term use of high-heeled shoes alters the neuromechanics of human walking”. In: *Journal of Applied Physiology* 112.6 (2012). PMID: 22241055, pp. 1054–1058. DOI: `10.1152/japplphysiol.01402.2011`. eprint: `https://doi.org/10.1152/japplphysiol.01402.2011`. URL: `https://doi.org/10.1152/japplphysiol.01402.2011`.

[28] Y.-J. Cha. “Analysis of Differences in the Degree of Biomechanical Adaptation according to Habituation to Different Heel Heights”. In: *TheScientificWorldJournal* 2020 (2020), p. 1854313. ISSN: 2356-6140. DOI: `10.1155/2020/1854313`. URL: `https://europepmc.org/articles/PMC7285271`.

[29] Y. D. Gu, J. S. Li, G. Q. Ruan, Y. C. Wang, M. J. Lake, and X. J. Ren. “Lower Limb Muscles SEMG Activity during High-Heeled Latin Dancing”. In: *6th World Congress of Biomechanics (WCB 2010). August 1-6, 2010 Singapore*. Ed. by C. T. Lim and J. C. H. Goh. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 198–200. ISBN: 978-3-642-14515-5.

[30] C. Li, Q. Mei, Y. Gu, and J. S. Baker. "Lower limb kinematics study on female Latin shoes of different heel heights". In: *International Journal of Biomedical Engineering and Technology* 18.4 (2015), pp. 301–309. DOI: `10.1504/IJBET.2015.071007`. URL: `https://www.inderscienceonline.com/doi/abs/10.1504/IJBET.2015.071007`.

[31] A. Barre and S. Armand. "Biomechanical ToolKit: Open-source framework to visualize and process biomechanical data". In: *Computer Methods and Programs in Biomedicine* 114.1 (2014), pp. 80–87. ISSN: 0169-2607. DOI: `https://doi.org/10.1016/j.cmpb.2014.01.012`. URL: `https://www.sciencedirect.com/science/article/pii/S0169260714000248`.

[32] S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen. "OpenSim: Open-Source Software to Create and Analyze Dynamic Simulations of Movement". eng. In: *IEEE transactions on biomedical engineering* 54.11 (2007), pp. 1940–1950. ISSN: 0018-9294.

[33] *Vicon Nexus Product Guide*. URL: `https://documentation.vicon.com/nexus/v2.2/Nexus1_8Guide.pdf` (visited on 05/02/2021).

[34] B. Svoboda and A. Kranzl. "A study of the reproducibility of the marker application of the Cleveland Clinic Marker Set including the Plug-In Gait Upper Body Model in clinical gait analysis". eng. In: *Gait & posture* 36 (2011), S62–S63. ISSN: 0966-6362.

[35] *SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) Project: Recommendations for sensor locations on individual muscles*. URL: `http://seniam.org/` (visited on 02/03/2021).

[36] *Mokka Documentation*. URL: `http://biomechanical-toolkit.github.io/docs/Mokka/index.html` (visited on 05/02/2021).

[37] *osimC3D Matlab Utility Description*. URL: `https://simtk-confluence.stanford.edu:8443/display/OpenSim/C3D+(.c3d)+Files` (visited on 05/04/2021).

[38] *OpenSim Documentation: Gait 2392 and 2354 Models*. URL: `https://simtk-confluence.stanford.edu:8443/display/OpenSim/Gait+2392+and+2354+Models` (visited on 05/04/2021).

[39] Z. Lerner, M. DeMers, S. Delp, and R. Browning. "How Tibiofemoral Alignment and Contact Locations Affect Predictions of Medial and Lateral Tibiofemoral Contact Forces". In: *Journal of Biomechanics* 48 (Jan. 2015). DOI: `10.1016/j.jbiomech.2014.12.049`.

[40] A. R. Lewis, W. S. Robertson, E. J. Phillips, P. Grimshaw, and M. Portus. "Estimating the Maximum Isometric Force Generating Capacity of Wheelchair Racing Athletes for Simulation Purposes". eng. In: *Journal of applied biomechanics* 35.5 (2019), pp. 1–365. ISSN: 1065-8483.

[41] *Matlab OpenSIM Libraries*. URL: `https://simtk-confluence.stanford.edu:8443/display/OpenSim/Scripting+with+Matlab#ScriptingwithMatlab-LoadingOpenSimLibraries` (visited on 05/04/2021).

[42] *OpenSIM IK Best Practice Recommendations*. URL: `https://simtk-confluence.stanford.edu:8443/display/OpenSim/Getting+Started+with+Inverse+Kinematics#GettingStartedwithInverseKinematics-BestPracticesandTroubleshooting` (visited on 05/04/2021).

[43] N. A. Bianco, C. Patten, and B. J. Fregly. “Can Measured Synergy Excitations Accurately Construct Unmeasured Muscle Excitations?” In: *Journal of Biomechanical Engineering* 140.1 (Nov. 2017). 011011. ISSN: 0148-0731. DOI: `10.1115/1.4038199`. eprint: `https://asmedigitalcollection.asme.org/biomechanical/article-pdf/140/1/011011/5988598/bio\_140\_01\_011011.pdf`. URL: `https://doi.org/10.1115/1.4038199`.

[44] G. (Bergmann. *Orthoload*. Charité Universitaetsmedizin Berlin. 2008. URL: `http://www.OrthoLoad.com` (visited on 05/09/2021).

[45] L. Modenese, E. Montefiori, A. Wang, S. Wesarg, M. Viceconti, and C. Mazzà. “Investigation of the dependence of joint contact forces on musculotendon parameters using a codified workflow for image-based modelling”. eng. In: *Journal of biomechanics* 73 (2018), pp. 108–118. ISSN: 0021-9290.

[46] J. Holder, Z. Feja, S. van Drongelen, S. Adolf, H. Böhm, A. Meurer, and F. Stief. “Effect of guided growth intervention on static leg alignment and dynamic knee contact forces during gait”. eng. In: *Gait & posture* 78 (2020), pp. 80–88. ISSN: 0966-6362.

[47] M. Sangeux, E. Passmore, H. K. Graham, and O. Tirosh. “The gait standard deviation, a single measure of kinematic variability”. eng. In: *Gait & posture* 46 (2016), pp. 194–200. ISSN: 0966-6362.

[48] H. Kainz, B. A. Killen, M. Wesseling, F. Perez-Boerema, L. Pitto, J. M. Garcia Aznar, S. Shefelbine, and I. Jonkers. “A multi-scale modelling framework combining musculoskeletal rigid-body simulations with adaptive finite element analyses, to evaluate the impact of femoral geometry on hip joint contact forces and femoral bone growth”. In: *PLOS ONE* 15.7 (July 2020), pp. 1–18. DOI: `10.1371/journal.pone.0235966`. URL: `https://doi.org/10.1371/journal.pone.0235966`.

[49] Y. Palmowski, S. Popović, and D. Kosack. “Analysis of hip joint loading during walking with different shoe types using instrumented total hip prostheses”. In: *Sci Rep* 11 (2021), p. 10073. DOI: `https://doi.org/10.1038/s41598-021-89611-8`.

[50] G. Giarmatzis, I. Jonkers, M. Wesseling, S. Van Rossom, and S. Verschueren. “Loading of Hip Measured by Hip Contact Forces at Different Speeds of Walking and Running: HIP LOADING MEASURED BY HCFS AT DIFFERENT SPEEDS OF WALKING AND RUNNING”. eng. In: *Journal of bone and mineral research* 30.8 (2015), pp. 1431–1440. ISSN: 0884-0431.

[51] R. Snow and K. Williams. “High heeled shoes: their effect on center of mass position, posture, three-dimensional kinematics, rearfoot motion, and ground reaction forces”. In: *Archives of physical medicine and rehabilitation* 75.5 (May 1994), pp. 568–576. ISSN: 0003-9993. URL: `http://europepmc.org/abstract/MED/8185452`.

[52] A. Mika, Ł. Oleksy, P. Mika, A. Marchewka, and B. C. Clark. “The Effect of Walking in High- and Low-Heeled Shoes on Erector Spinae Activity and Pelvis Kinematics During Gait”. In: *American Journal of Physical Medicine & Rehabilitation* 91 (5 2012), pp. 425–434. DOI: `10.1097/PHM.0b013e3182465e57`.

[53] J. Schroeder and K. Hollander. “Effects of high-heeled footwear on static and dynamic pelvis position and lumbar lordosis in experienced younger and middle-aged women”. eng. In: *Gait & posture* 59 (2018), pp. 53–57. ISSN: 0966-6362.

[54] D. Gravel, C. Richards, and F. M. “Angle dependency in strength measurements of the ankle plantar flexors”. eng. In: *Eur J Appl Physiol Occup Physiol* 61.3-4 (1990), pp. 182–187. DOI: `10.1007/BF00357596`.

[55] K. Manal, D. P. Roberts, and T. S. Buchanan. “Optimal pennation angle of the primary ankle plantar and dorsiflexors: variations with sex, contraction intensity, and limb”. eng. In: *Journal of applied biomechanics* 22.4 (2006), pp. 255–263. ISSN: 1065-8483.

[56] S. Farr, A. Kranzl, E. Pablik, M. Kaipel, and R. Ganger. “Functional and radiographic consideration of lower limb malalignment in children and adolescents with idiopathic genu valgum”. eng. In: *Journal of orthopaedic research* 32.10 (2014), pp. 1362–1370. ISSN: 0736-0266.

[57] H. Böhm, F. Stief, K. Sander, M. Hösl, and L. Döderlein. “Correction of static axial alignment in children with knee varus or valgus deformities through guided growth: Does it also correct dynamic frontal plane moments during walking?” eng. In: *Gait & posture* 42.3 (2015), pp. 394–397. ISSN: 0966-6362.

[58] E. M. Wanke, J. Schreiter, D. A. Groneberg, and B. Weisser. “Muscular imbalances and balance capability in dance”. eng. In: *Journal of occupational medicine and toxicology (London, England)* 13.1 (2018), pp. 36–36. ISSN: 1745-6673.