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The implication of backward walking in the rehabilitation of neuro-musculoskeletal conditions: systematic reviews and a biomechanical movement analysis

Tharani Balasukumaran

A thesis submitted to the Faculty of Health Science, University of the Witwatersrand, in fulfilment of the requirements for the degree of

Doctor of Philosophy in Physiotherapy

Johannesburg, South Africa – 2018

Declaration

I, Tharani Balasukumaran declare that this thesis is my own work. It is being submitted for the degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at this or any other University.



[Signature of candidate] Date: 07.05.2018

Abstract

The neuro-musculoskeletal gait impairments have an enormous and growing impact in the world. Estimation shows that one in four people suffer from gait impairments as a major limitation. It reduces the quality of life with poor balance, muscle fatigue, joint stiffness and deformity. To treat neuromuscular gait impairments proper rehabilitation training is crucial. Walking is one of the functional training used by therapist for rehabilitation. Though, walking refers a forward walking (FW) in our daily life backward walking (BW) was reported for an effective functional exercise in rehabilitation. The underlying biomechanical characteristics such kinetic and kinematic parameters of both FW and BW were studied to understand and predict the clinical benefits.

Biomechanical characteristics of FW were studied extensively with respect to speed, inclination, and surface. Whereas, limited reports on BW were found with level and uphill walking with comfortable/fixed speed on both ground and treadmill. It is important to study biomechanical characteristics with respect to speed and inclination to understand neural control strategies and musculoskeletal activities during BW. This helps to evaluate their clinical worthiness before implementing on patients. The comparison of FW with BW as a systematic review is an optimum way to reveal their clinical benefits and unique changes in locomotion task. As there is no systematic review is available in the literature, the present thesis designed with two systematic reviews and an experimental study.

In brief the methodologies followed in this thesis were as follow: The two systematic reviews identified existing literature based on a structured search strategy applied to various databases. The outcomes were statistically analysed by RevMan software. For experimental study, 3D-kinematic movements were tracked by reflective markers using Qualisys cameras. Force plate integrated treadmill was used to measure GRF and muscle activities were recorded by wireless EMG. These Qualisys camera, treadmill and EMG were synchronised with QTM software. The collected data were analysed and processed through Visual3D software. The processed data were used to simulate an anthropometric model via OpenSim software. This software was used to calculate the kinematic and kinetic parameters.

The first systematic review in Chapter-3 explores the clinical effectiveness of BW as a functional training for neuro-musculoskeletal gait impairment condition. This review dealt with six types of comparison with BW as an experimental group. The systematic search strategy finalises the eight trials with three conditions such as knee osteoarthritis (OA), stroke, and diabetic peripheral neuropathy. The primary outcome measures were the pain, functional disability, muscle strength, gait parameters, balance and plantar pressure. The results show BW with CPT was significantly effective in reducing knee OA pain (total SMD: -0.87), lowering

functional difficulties (total SMD: -1.39) and improving muscle strength (SMD: 1.51). In conclusion BW with CPT is an effective and clinically worthwhile training for rehabilitation of knee OA.

The second systematic review in Chapter-4 deals with biomechanical characteristics BW through comparison of FW for healthy participants to understand neuromuscular contributions. Twenty trials were found through systematic search strategy for kinematic and kinetic outcomes. The results show that BW significantly different from FW with lower hip flexion, knee flexion, tibiofemoral joint reaction force, ankle joint power, hip joint power, GRF and temporal gait parameters. The muscles GM, BF, RF, and LGAS are more active in BW than FW. Hence, the modified neural control strategies were required to produce BW from FW. The absence of visual cues in BW improves the neuromuscular control, proprioception and protective reflexes. Among the trials, BW in water found to be safer and yields better results than ground and treadmill.

The experimental study in Chapter-5 analysed biomechanical characteristics of FW and BW with controlled speed and inclination. Ten healthy participant were chosen for FW and BW in three inclinations (-5%, 0% and +5%) and speeds (0.28 m/s, 0.69 m/s and 1.11 m/s). The study concludes that, walking speed is directly related to energy requirements. Increasing the speed requires higher magnitudes of the joint moment, joint power and muscle activity irrespective of inclination and direction. In FW and BW, uphill and downhill task produces opposite joint moment with a variety of flexor and extensor muscles contributions. These indicate that the motor control task requires different control strategies for inclined walking. The anatomical constraint and visual cues give additional features in biomechanical parameters of BW. Hence, a simple time reversal is not sufficient to distinguish between BW and FW. Interestingly, the similarities were observed between FW uphill and BW downhill or FW downhill and BW uphill in hip/knee joint moment and muscle activities. Such as during FW uphill and BW downhill an extension moment was present at the hip joint and a flexion moment at the knee joint. Here, the biarticular muscles BF was active in both types of walking. But we cannot conclude both types of walking were controlled by the same neural network as power patterns were distinctly different. The distributions of total power flow among joints were found to be related to the posture associated with the inclination in both FW and BW. Ankle contribution is more in both FW uphill and BW downhill (leaned trunk) whereas hip contributes for FW downhill and BW uphill (erected trunk). In level walking ankle dominates in both FW and BW irrespective of speeds. The ankle joint had main propulsion at all inclination and speed during FW and BW except FW uphill.

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Publications and presentations arising from this study

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Tharani Balasukumaran, Benita Olivier and Veronica Ntsiea 2018 The biomechanics of backward walking is not just a simple reversal of forward walking: a systematic review. (Submitted to Gait &Posture journal)

Congress presentations:

Tharani Balasukumaran, Benita Olivier, and Veronica Ntsiea The speed of backward walking – A kinematic study in international level conference, 20th European Congress of Physical and Rehabilitation Medicine, Portugal 2016 - Poster Presentation

Tharani Balasukumaran, Benita Olivier, Veronica Ntsiea and Andrews Green. Joint angles and gait parameters during backward walking at various walking speed in wits 6th Cross – faculty graduate symposium, University of the Witwatersrand, South Africa 2014 - Poster Presentation

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List of abbreviations

ANOVA - Analysis of variance

BBS - Berg balance scale

BF - Biceps femoris

BMI - Body mass index

BW - Backward walking

CMC - Computed muscle control

CoP - Center of pressure

CoM - Center of mass

CPT - Conventional physiotherapy treatment

dh - downhill

DPN - Diabetic peripheral neuropathy

DLS - Double limb support

EMG - Electromyography

FD - Functional disability

FW - Forward walking

GM - Gluteus maximus

Gmed - Gluteus medius

GRF - Ground reaction force

HAM - Hamstring

IK - Inverse kinematics

IL - iliacus

JBI-MAStARI - Joanna Briggs Institute Meta-Analysis of Statistics Assessment and Review Instrument

LGAS - Lateral Gastrocnemius

MT - Meta tarsal

NPRS - Numerical pain rating scale

OA - Osteoarthritits

PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PS - Paraspinal

RF - Rectus femoris

RoM - Range of motion

RRA - Residual reduction algorithm

RMS - Root mean square

rWOMAC - reduced Western Ontario and McMaster Universities Arthritis Index

SMD - Standardised mean difference

SOL - Soleus

ST - Semitendinosis

TA - Tibialis anterior

TFJRF - Tibio femoral joint reaction force

uh - uphill

VAS - Visual analogue scale

VL - Vastuslateralis

VM - Vastusmedialis

WHO - World health organisation

WOMAC - Western Ontario and McMaster Universities Arthritis Index

Definition of terms

Biomechanics: In humans, biomechanics often refers to the study of how the skeletal and musculature systems work under different conditions. Moreover, it often applied by physics and mathematically based forms of analysis to discover the internal and external forces acting on the human body and the effects produced by the forces (1).

Kinematics: The study of the motion of the body without regard to the force acting to produce motion. In human movement, it is the study of the positions, angles, velocities and accelerations of the body segments and joint during motion (1).

Kinetics: The study of the forces that produce, stop or modify the movement. In human movement, kinetics deals with internal and external forces and their derivatives such as, moment, power, and muscle activity of the body segments and joints during motion (1).

Moment: It is produced when forces are applied in a rotational system. They are called moment of force. Moment is vectors and therefore has both a direction and a magnitude. Joint moment that we measure is the net effect of the positive agonist muscle force and the negative antagonist muscle forces and their associated moment arm lengths. It's calculated by multiplying the perpendicular force by the distance from the axis of rotation. Resistance in strength training produces an external moment, whereas muscles produce an internal moment to counteract the external moment. These are more properly called net joint moment (2).

Power: Power is defined as the rate of work or rate of energy flow. It is calculated either by dividing work by time or by multiplying force by velocity. Joint power is the scalar product, it is possible to measure the power output of individual joints during movement by multiplying the torque by the joint angular velocity (3,4).

Forward walking: Human walk/forward walk refers to locomotion achieved to movement of human limbs. Forward walking is defined as bipedal, biphasic forward propulsion of center of gravity of the human body, in which there are alternate sinuous movements of different segments of the body with least expenditure of energy (5).

Backward walking: Backward walking is the act of walking in reverse, so that one travels in the direction one's back is facing rather than one's front. It is a less natural motion and classed as a retro movement (6)

Model: A model as a set of mathematical equations that describe a physical system. The physical system is the human or animal neural and /or muscular system acting on a rigid multi-body skeletal structure (7).

Simulation: Simulation is the imitation of the operation of a real-world process or system over time. The act of simulation for walking starts with a development of an anthropometric model followed by the analysis of inaccessible muscles and joints with accurate dynamic parameters (7). Here, the anthropometric model consists of the collected experimental data, bone geometry, joint geometry, muscle geometry, body segments, and muscle actuators.

Muscle activity: A tissue composed of bundles of elongated cells capable of contraction and relaxation to produce a movement in an organ or part (8). Muscle contraction is the activation of tension-generating sites within muscle fibers. This muscle movement was recorded through electromyography. An electromyography detects the electric potential generated by muscle cells. When these cells are neurologically activated, the signals can be analysed to detect the activity of muscles (9).

CHAPTER 1 - Background and significance of the study

1.1 Introduction

A physically active society produces a healthy and prosperous world (10). The 2016 World Health Organisation (WHO) report stated that in global population, physical inactivity has been identified as the fourth leading risk factor for global mortality causing an estimated 3.2 million deaths globally (11–13). Estimation shows that one in four people suffer from gait impairments as a major limitation in their quality of life (14,15). The deviations from normal walking arise from the common problems from both nervous system and musculoskeletal system. Hence, the gait abnormalities were considered as a neuro-musculoskeletal disease which can be characterized by the combinations of strength, sensation, and coordination (16).

In general, human movement is produced by coordination of muscles and joints (17). Here, the task-specific signals were received from central pattern generator designed by appropriate neural control strategies to coordinate the biomechanical movements (18). Over the years, biomechanical studies investigated the human movements through joint kinematics, joint kinetics, and muscle activities to evaluate neural control strategies (19–24). Estimation of these biomechanical parameters and understanding their nature in neural control perspective found to be useful for disease-specific clinical guidance (22,23,25,26). Neuro-musculoskeletal conditions such as Parkinson's diseases, multiple sclerosis, peripheral neuropathy, stroke, osteoarthritis, and muscle insufficiency etc., mainly affects the gait parameters such as cadence, step length, functional disability, poor balance, in-coordination, joint stiffness and deformity (27). To rehabilitate these biomechanical gait parameters, therapists give forward walking (FW) as well as backward walking (BW) training as a functional exercise. The emergence of novel simulation studies in biomechanical motion analysis of the human body enhanced the understanding of rehabilitation (28). Three-dimensional simulation studies that accurately reproduce human gait provide deeper insight into motion dynamics. The essential gait characteristics are broadly categorised into kinematics and kinetics. Between these properties kinematics are directly calculated by vector analysis from experimental data (29), however, model development and inverse dynamic simulations are required to calculate accurate kinetic parameters (30). For example, the simulations will establish accurate dynamic parameters for the experimentally inaccessible muscles.

Simulation studies combined with experimental observation have examined the biomechanical characteristics of the lower limb during FW with respect to speed and inclination (31–35).

Whereas, BW related data is insufficient to establish the joint and muscle characteristics (36,37). It is important to note that BW involves additional neural controls and more musculoskeletal demands in comparison to FW. Hence, an in-depth understanding of BW is needed before clinical implementation can be considered. The controlled experiments of BW at different inclinations and at different speeds will be necessary to understand the BW patterns. In the present study, existing data in literature for BW were systematically reviewed and the experimental study with simulations was pursued to determine the effectiveness and biomechanical characteristics of BW.

1.2 Problem statement

Extrapolated data show that globally more than 30.9 million people are affected by the musculoskeletal disease and one billion people affected by neurological disease. The 2010 to 2014 statistical reports from the global burden of diseases indicate that low back pain (83million), rheumatoid arthritis (4.8million), osteoarthritis (50million), stroke (15million), Parkinson's disease (7-10million), multiple sclerosis (2.3million), Alzheimer's disease and dementia (36million) were exist among global population (31–35). The WHO report stated that "in global population, physical inactivity leads to 1.9 million deaths and the loss of 19 million disability-adjusted life years". These diseases are associated with common functional limitations which include difficulty in walking.

Recent experimental studies show that BW is effective in functional training when combined with conventional physiotherapy for neuro-musculoskeletal related gait impairments (21,36–38). Over the years, the improvements due to BW were reported inconsistently for clinical outcomes such as pain, functional disability, muscle strength and balance. Moreover, the reports on clinical applications and biomechanical characteristics of different type of BW such as speed, inclination and environmental changes were not understood as like FW. The calculation of biomechanical characteristics such as kinematic and kinetic parameters can provide neural control strategies, joint and muscle characteristics (39–41). This will add understanding to prescribe appropriate BW in various populations. For example, BW training needs more muscle activity along with smaller flexion and adduction moment at knee during stance phase of gait. These kinetic characteristics were reducing disability of knee joint movement during BW at slow speed which helped to yield higher functional ability than FW (36,42). Hence the problem statement of the present thesis pertains to the need for both the effectiveness of BW in neuro-musculoskeletal gait impairment conditions as well as the biomechanical characteristics of BW to be systematically reviewed from existing literature. Here, the study of BW may give a better

understanding during appropriate comparison with FW. Calculating biomechanical components like joint angle, joint moment, joint power and muscle activity during BW at various inclinations and at different speeds will assist filling the gap of experimental findings in literature.

1.3 Research question

1. What is the clinical effectiveness of BW in the treatment of neuro-musculoskeletal related gait impairments?
2. What is the difference in the kinematic (joint angles) and kinetic (joint moment, joint power and muscle activity) characteristic of FW and BW during a gait cycle at different inclinations and speeds?

1.4 Aim of study

The aim of this study were,

1. To establish the clinical effectiveness of BW in the treatment of neuro-musculoskeletal related gait impairments.
2. To describe the difference in the kinematic (joint angles) and kinetic (joint moment, joint power and muscle activity) characteristics of FW and BW during a gait cycle at different inclinations and speed based on a systematic review.

1.4.1 Objectives of the study

The above aim will be accomplished by fulfilling the following research objectives:

1. To establish the effectiveness of BW in the treatment of neuro-musculoskeletal gait impairments in the form of a systematic review and meta-analysis.
2. To compare the existing biomechanical characteristics of BW with FW in the form of a systematic review.
3. To understand neural control strategies during FW and BW through calculation of biomechanical characteristics such as the kinematic parameters (joint angles) and the kinetic parameters (joint moment, joint power and muscle activity) by simulation at three levels of treadmill inclination and speed.

1.5 Significance of the study

The exploration of the effectiveness and biomechanical characteristics of BW is essential as 64% of the South African population (43) suffers from musculoskeletal disease and 20% of the global population (44) is affected by neurological diseases. The present study aimed to identify the effect of BW in the treatment of neuro-musculoskeletal related gait impairments and to evaluate the biomechanical parameters of healthy people during BW. This study analysed FW and BW at various speed and inclination to find the kinematic and kinetic parameters of lower limb to understand the neural control strategy for FW and BW. These biomechanical parameters are necessary to develop neuro-musculoskeletal exercise programmes to understand the internal structure and function of the joint, and muscle activity patterns. In addition to the experimental results, the systematic reviews will serve as a knowledge source for clinical practitioners and researchers to treat the patients and to develop further protocols for related conditions and interventions. This thesis consists of various chapters which include the background and significance of the study (Chapter 1), the narrative literature review (Chapter 2), followed by two systematic reviews (Chapter 3 and 4) and a simulation study (Chapter 5). The three phases of the study are as follow:

- The effectiveness of backward walking as a treatment for people with gait impairment: a systematic review and meta-analysis (Chapter 3)
- The comparison of biomechanical characteristics of backward and forward walking: A systematic review (Chapter 4)
- The kinematics and kinetics during forward and backward walking at three levels of treadmill inclination and speed: A simulation study (Chapter 5)
- At the end of this thesis a conclusion chapter is presented in Chapter 6

CHAPTER 2 - Literature review

2.1 Introduction

Impairments to the neuro-musculoskeletal gait are proving to have reached enormous proportions globally and also have had a growing impact on human life (45). The functional limitations arising from gait impairment reduce the ability to move and diminish physical fitness (46). To achieve improved functional levels in their patients, therapists have introduced the action of walking into their rehabilitation programmes (47). The types of training applied in improving the gait, where surface, speed, inclination, and the direction of walking are crucially important variables have been a prescribed in terms of the symptoms of the disease suffered by the patient (48–50). The appropriate type of training has an important role to play in the rehabilitation of the patient. In this respect, the numerous reports presented in the literature also contributed significantly to an understanding of the characteristics of walking (20,47,51). These reports, based on both experimental and simulation studies, also included the clinical implications of neuro-musculoskeletal diseases like, osteoarthritis, stroke, Parkinson's, cerebral palsy etc., (52–55).

This chapter sets out to review the current literature pertaining to the underlying conditions of neuro-musculoskeletal related gait impairments, the importance of walking during the rehabilitation phase, and the methods used to evaluate the biomechanical characteristics of gait. A statistical analysis of FW and BW can be found in Chapters 3 and 4, which are both systematic reviews. Chapter 3 is concerned with the effectiveness of backward walking in the treatment of neuro-musculoskeletal related gait impairments and Chapter 4 is concerned with the biomechanics of backward and forward walking. In order to avoid repetition, the reader is at times referred to these two chapters for detailed information.

The search strategies were designed to find both published and unpublished studies in all languages and time periods for inclusion in this thesis. Both experimental and non-experimental studies were considered, and the following databases were searched: PubMed, MEDLINE Scopus, and Google Scholar. The following keywords were used to source the literature referred to in this literature review: walking, gait impairment, gait abnormality, strengthening, stretching, electrotherapy modalities, functional exercise, backward walking, retro walking, neurological diseases, musculoskeletal disease, inclination, speed, motion analysis, and gait analysis. Table 2.1 shows the search strategy through PubMed.

Table 2.1 Literature review search strategy

Recent queries in pub med

Search	Query	Items found	Time
#31	Search (musculoskeletal disease) AND ((backward) AND walking)	25	18:51:49
#30	Search (neurological disease) AND ((backward) AND walking)	176	18:51:14
#29	Search (walking) AND motion analysis	5186	18:50:27
#38	Search (((backward) AND walking)) AND speed	192	18:49:42
#27	Search (((backward) AND walking)) AND inclination	20	18:48:42
#26	Search (walking) AND inclination	304	18:48:27
#25	Search inclination	8568	18:47:55
#24	Search ((neurological disease) AND gait) AND impairment	2249	18:46:57
#23	Search (neurological disease) AND gait abnormality	460	18:46:15
#22	Search ((musculoskeletal disease) AND gait) AND impairment	335	18:45:38
#21	Search (musculoskeletal disease) AND gait abnormality	184	18:45:14
#20	Search (functional exercise) AND ((walking) AND gait)	2214	18:44:39
#19	Search (((walking) AND gait)) AND speed	6950	18:43:54
#18	Search (backward) AND walking	763	18:43:26
#17	Search (((walking) AND gait)) AND ((backward) AND retro)	1	18:42:59
#16	Search (backward) AND retro	21	18:42:17
#15	Search (walking) AND gait	29173	18:42:01
#14	Search gait analysis	18078	18:41:34
#13	Search motion analysis	64265	18:41:20
#12	Search speed	173501	18:41:04
#11	Search functional exercise	29505	18:40:36
#10	Search electrotherapy modalities	2086	18:40:16
#9	Search strengthening	23220	18:39:45
#8	Search musculoskeletal disease	992333	18:39:15
#7	Search neurological disease	2559730	18:38:55
#6	Search gait abnormality	744	18:38:00
#5	Search retro	6231	18:36:32
#4	Search backward	17234	18:36:25
#3	Search impairment	244615	18:36:09
#2	Search gait	50190	18:34:53
#1	Search walking	80031	18:34:45

2.2 Neuro-musculoskeletal gait impairment conditions

Normal gait requires a delicate balance between various interactions of the neurological and the musculoskeletal system and it involves locomotion, rhythmic stepping, and balance. Dysfunction in any of these systems can disturb gait. Most of the neurological and chronic musculoskeletal problems are caused by dysfunctions in a number of systems (e.g. the passage of signals from the brain to the peripheral nerves, and from the peripheral nerves to the muscles, rather than by the supportive system of bones, joints, and ligaments (56,57).

The neurological gait impairment conditions include Parkinson's disease, stroke, cerebral palsy, multiple sclerosis, Alzheimer's disease, and dementia (58–60). Neurological gait impairments are due to focal or diffuse lesions along the neural pathways between the cortical motor centre and the peripheral neuromuscular systems. The signs and symptoms include numbness, a tingling sensation, muscle spasm, imbalance, incoordination, reduced muscle tone and muscle strength (56,57,61).

The musculoskeletal conditions also lead to gait impairments which affect the functional ability of the lower limb muscles. Common conditions around musculoskeletal gait impairments are knee bursitis, Achilles and patellar tendonitis, low back pain, repetitive ankle strain, muscle insufficiency, osteoarthritis and rheumatoid arthritis (62–64). To elaborate on arthritis we quote the following example: "arthritis mainly affects the synovial joints and involves damage to the articular cartilage. In the acute phase, this cartilage damage leads to increased joint friction, which causes pain, swelling and joint stiffness" (62,65,66). The sustained cartilage damage eventually leads to walking difficulties (62,65,66). To address a neuro-musculoskeletal related gait impairment, proper gait assessment and rehabilitative training are crucial (67–69).

2.3 Rehabilitation of neuro-musculoskeletal gait impairment

To rehabilitate the gait impairment problem, therapists provide conventional treatments such as stretching to relieve the joint stiffness and improve soft tissue mobility (58,70,71), muscle strengthening exercises to improve muscle control (66,70,72), and heat therapy to reduce pain and swelling (36,73,74). Over the years, walking was found to be an important exercise in the treatment of neuro-musculoskeletal gait impairments (60,74–79). In rehabilitation programmes, training in forward walking (FW) and backward walking (BW) was incorporated along with conventional treatments to improve the participants' walking pattern (36,38,41,47,52,54,70,80,81).

Research into BW has been conducted only in the past 30 years (39,82). The first published BW study came from Thorstensson (1986), who compared joint angles and muscle activity during FW and BW. The results of his study indicate that the joint angles are similar in both types of walking but that the muscle activity patterns tend to change with respect to the gait phases (82). For the lower limb muscles, BW brings with it an increased amount of knee extensor activity in the loading response phase to enhance the muscle strength of the quadriceps (25,48). The increased strength in the quadriceps muscle tends to reduce the pain in the patella and the femur. Other researchers found this to be the case mainly during BW rather than during FW (36,83).

Dufek et al (84) concluded that BW may reduce low back pain and enhance function for athletes. Backward walking has also shown to bring about an improvement in general fitness (41,85), a reduction in patella femoral pain (21,73,81,86), an increment in muscle strength, a reduction in joint stress (87) and an improvement in balance (88–90). In essence, the clinical outcomes reported in the literature reveal the benefits of BW and its importance in a rehabilitation programme.

Walking is inherently unstable motor task as it requires sophisticated neurological control systems with active feedback system. Biomechanical studies investigated the human movements through joint kinematics, joint kinetics, and muscle activities to evaluate neural control strategies (19–24). Estimation of these biomechanical parameters and understanding their nature in neural control perspective was found to be useful for disease-specific clinical rehabilitation (22,23,25,26).

Hackney et al (52,91) compared 78 idiopathic Parkinson patients with 74 normal participants. Here, participants from both groups walked forward and backward on the ground. The results showed that the temporal and spatial gait parameters were reduced with higher double limb support and improved postural stability and that the BW group benefited more in this respect than the FW group. Tseng et al (92) found that BW enhances balance and improves gait in the case of the participants with Parkinson disease.

Shaji et al (93) conducted a study with 30 participants with hamstring strains (Grades 1 and 2). Here, the participants were divided into two groups: the experimental group, which performed BW with conventional treatment and the control group, which performed FW with conventional treatment. The result reported that quadriceps and ankle plantar flexor strength improved when BW was included in the programme.

In the present study, the systematic review in Chapter 3 explores the effectiveness of FW and BW in clinical outcomes as gleaned from the available literature. The results show statistical significance in the reduction of pain, an increased range of motion, increased muscle strength and functional ability when BW is supplemented with a conventional treatment programme instead of FW.

2.4 Biomechanical characteristics of FW and BW

The clinical importance of forward and backward walking as a functional exercise caused this researcher to be motivated to study their impact on lower limb biomechanics under conditions where the direction and speed of walking and the inclination of the walking surface are changed. The study of biomechanical characteristics facilitates an understanding of the kinematics and kinetics of lower limb musculoskeletal movements, along with neural control strategies. In this study, the kinematic data were directly obtained from a motion capture system; whereas the kinetic data were acquired through the application of an inverse dynamics approach. The detailed methods of forward and backward walking are set out below.

2.4.1 The kinematics of forward and backward walking

Kinematic characteristics such as joint angles are evaluated from the gait phases (Figure 2.1). In a gait cycle, FW starts from heel strike and ends with toe off (25,39,40,82,94–96). During FW heel strike (0%),the hip, knee and ankle show flexion, extension, and dorsiflexion respectively, while in the midstance to pre-swing phase (30% to 60%), hip extension, knee decreased flexion, and ankle decreased dorsiflexion are occurred.

The BW gait phase starts from toe strike to heel off (25,39,40,82,94–96). The BW kinematics of the hip, knee, and ankle initially show extension and plantar flexion at toe strike. During the midstance to pre-swing phase, hip flexion, knee flexion, and ankle dorsiflexion are experienced.

Thorstensson (1986) compared joint angle and muscle activity during FW and BW. The results indicate that the joint angles are similar in both forward and backward walking but that the muscle activity patterns changes with respect to the gait phases (82). The other experimental studies are also in agreement in respect of this concept(25,39,40,82,94,97,98). For example, the hip joint angle during BW exhibits a simple temporal reversal of what occurs in FW. It seems, therefore, that the kinematic patterns in BW are a mirror image of those in FW (39,82).

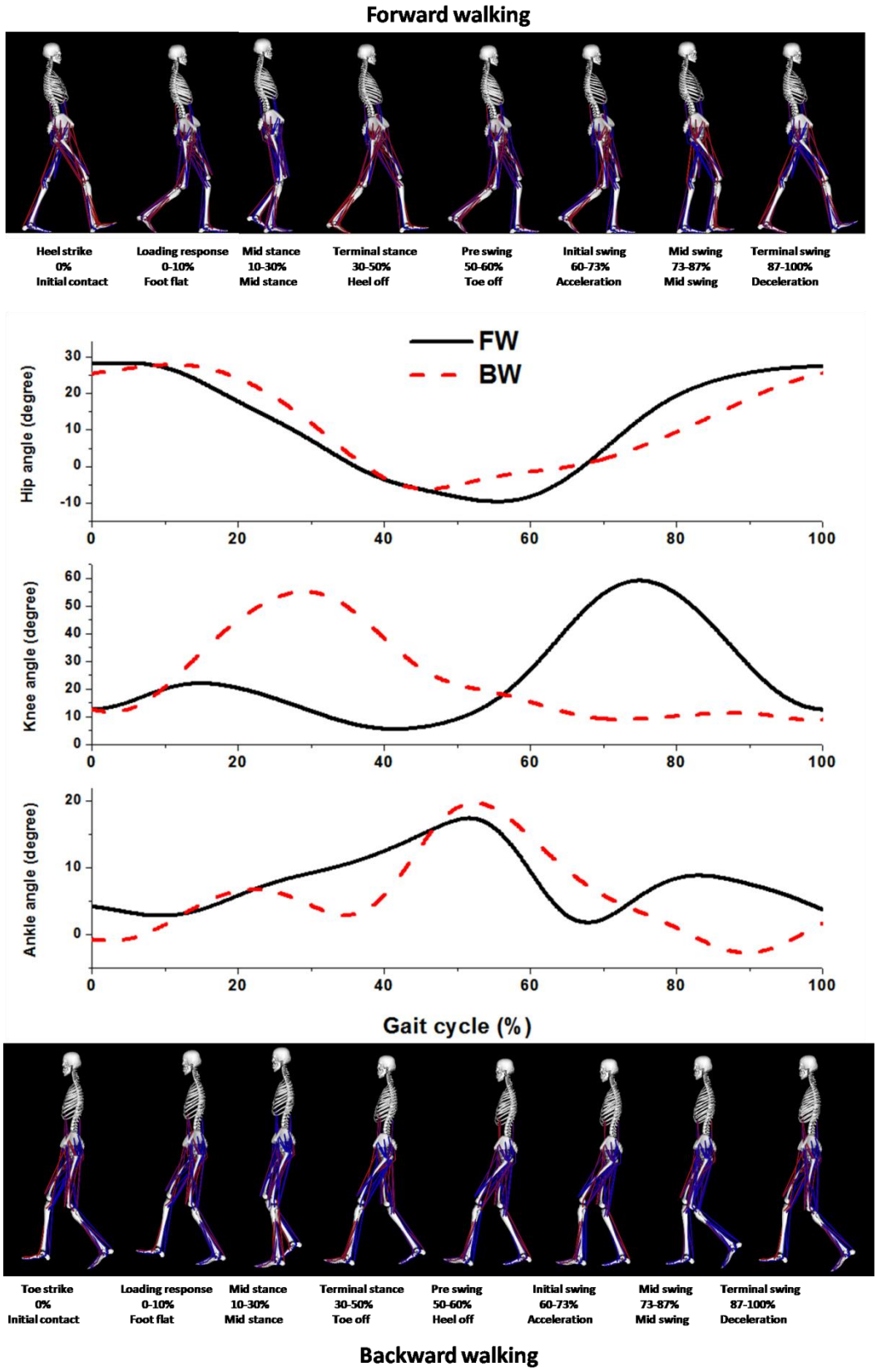

Figure 2.1 The forward and backward walking gait phases with lower limb joint angles. Here, solid black line: forward walking and dotted red line: backward walking

2.4.2 The kinetics of forward and backward walking

The kinetic parameters of walking include joint moment, joint power and muscle activity. In the analysis of FW, the hip and knee joints showed both flexion and extension moment, while the ankle joint showed plantar flexion moment. The net joint power of the ankle showed greater power generation than the knee and the hip joints which were found to generate less power (1,18,99,100,100–103). The hip extensor gluteus and the hamstring muscles, the hip flexor iliopsoas, the knee flexor biceps femoris and the extensor quadriceps, the ankle dorsiflexor tibialis anterior, and the plantar flexor gastrocnemius and soleus muscles were found to be active during FW (25,50,104).

During backward walking, the upper leg muscles showed more-or-less similar activation patterns to those for FW, but a complete shift took place in the activation patterns of the lower leg dorsiflexor and plantar flexor (25,40).

Hence, the changes in the contributions that the muscles make to walking imply that a simple time reversal would be insufficient to reproduce the kinetic patterns of BW from those of FW (25,40,82). Only three studies were found that compared the kinetic analysis of FW and BW (23,40,105). The reader is referred to Chapter 4, which presents a statistical comparison of the reported kinetic parameters for FW and BW.

2.4.3 Effect of speed and inclination on FW and BW

Several experimental and simulation studies on the biomechanical characteristics of the lower limb during FW with respect to speed and inclination have been reported in the literature (50,55,101,102,104,106). In the case of the lower limb, the walking speed enhances both vastusmedialis and soleus muscle activity and also increases the joint range of motion (ROM) (102,107). The greater knee flexion in the stance phase during fast speed walking causes increased vasti force, which provides support but also slows progression, while the contralateral soleus simultaneously provides support to increase propulsion (102).

Another study found that when the walking speed increases, the rectus femoris, tibialis anterior and biceps femoris muscles show substantial changes in their amplitude at a specific speed. However, while reducing the speed of walking, negative gain value were found in the peroneus longus and the rectus femoris muscles. It was found that these negative gain value of energy absorption help to increase postural stability and to alter the dynamics of the swinging limb at a very slow speed (20).

Chi et al (19) reported that an increased walking speed causes significant increases in the muscle activity, as well as a vertical ground reaction force in the loading response and the mid-stance phases. Four studies reported BW muscle activity in relation to walking speed. They reported that an increased walking speed causes a significant increase in muscle activity (24,108–110).

Walking on an inclined surface changes the kinetic parameters. Walking on an up/downslope exhibits a significantly increased joint moment as opposed to walking on a level surface. The increased joint moment is predominantly due to the higher hip extensor moment during upslope walking and increasing knee extensor moment during downslope walking (18,111,112). Another study identified the peak moment and found that muscle power in the knee joint is much greater during downhill walking than is the case with muscle power in the ankle and the hip (18,50).

McIntosh et al (113) reported that the raising and lowering of the centre of mass prevent falls in uphill and downhill walking. The research concerning FW was found to be associated with muscle and joint mechanisms in the lower limb (e.g. muscle activity, muscle power, joint angle, joint moment, joint force and joint power with respect to speed and inclination).

Only three studies reported backward uphill walking and none reported downhill BW. In these studies, it was found that the activity levels of the rectus femoris and gastrocnemius muscles increase in uphill BW (22,24,48). For an in-depth understanding, the reader is referred to Chapter 5, which explains the biomechanics of FW in terms of the three levels of inclination and speed selected for this study, as opposed to those of BW.

2.5 Biomechanical analysis of FW and BW

2.5.1 Data capturing

Nowadays, movement laboratories are using advanced motion capture systems (52). Earlier, videos were used to analyse motion, as in the case of Kinovea and Tracker's software, which includes free 2-D video analysis and modelling tools (114). This software calculates only the kinematics of body movements such as position, velocity, and acceleration. On the other hand, the development of a 3-D motion-capturing system allows us to evaluate kinetic parameters. Most of the 3-D motion-capture systems and software are available only in the commercial market (e.g. AMASS [C-motion Inc., Kingston, Canada], Vicon [Vicon, Oxford, UK], and Qualisys Track Manager [Qualisys Medical AB, Gothenburg, Sweden]). Here, movements are captured by synchronised cameras to construct a 3-D motion from reflective markers. AMASS software does not have the synchronisation options for force plate and electromyography

(EMG), whereas the advanced motion capture systems, Vicon and Qualisys, are integrated with force plates, EMG and a number of other devices.

In Chapter 5 of this thesis, the Qualisys system was used to synchronise the Qualisys camera for a 3-D marker position, the Bertec instrumented treadmill for ground reaction force, and the Delsys EMG for muscle activity. In this study, the default error for the Qualisys camera marker prediction was 30mm. As such, the marker distance intervals selected for this study amounted to more than 30mm. The default value of the maximum residual was 10mm. The value for the parameter can usually be set at two to five times the average residual value in the calibration result for the camera system (115). The Bertec treadmill has two belts which can be controlled independently, each half having its own six-load measurement component (Fx, Fy, Fz, Mx, My, Mz) for the uphill and downhill analysis of movements up to 15 degrees within a speed range of 0-24 km/hour (116). The Delsys trigno wireless EMG has a signal range of ± 5V with less than 0.5 mV baseline noise (117).

2.5.2 Modelling and analysis

MATLAB (25,82) and Visual3D are popular modelling tools for experimental data (114). For this research, MATLAB was selected for it's a high- performance language for technical computing. It uses the versatile programming language developed by the MathWorks Inc. (NatickMA, 2000). Modelling and data analysis in MATLAB require high-level programming skills.

Visual3D, also used in this research, is a type of software for commercial modelling and data analysis. It has a comprehensive research platform for advanced modelling, signal processing, and analysis. It is the only type of software which allows the user to export OpenSim compatible motion files for musculoskeletal modelling. Visual3D was used in this study to build an anthropometric model with six degrees of freedom from a data set obtained from the Qualisys system (118). The kinematic (joint angle) and kinematic (joint moment and joint power) parameters were calculated through standard protocol (119,120). Chapter 5 explains in detail how Visual3D software was used to build the model from experimental data in order to create OpenSim compatible files.

2.5.3 Musculoskeletal simulation

For nearly 40 years, musculoskeletal simulation procedures have been used to understand the coupling between dynamic mechanics and estimates of muscle and joint loading (121). Over the past decade, simulation studies have been rapidly evolving thanks to an increase in software available for musculoskeletal modelling and algorithms, as well as to increased computing power (102,122).

There have been several studies in which the researchers chose to develop their own mathematical programmes to run the simulation of movement data (123–125). SIMM, LifeMod, AnyBody, and OpenSim are software packages commonly used in research. SIMM, a type of commercial software was used in the early 1990s. It makes it possible for users to create, alter and evaluate models of many different musculoskeletal structures (126). LifeMod and AnyBody, also types of commercial software; do not provide full source codes which makes it difficult for researchers in biomechanics to extend their capabilities (122).

Delp et al (122) developed OpenSim as an open-source platform for modelling, simulating, and analysing the neuro-musculoskeletal system. OpenSim was developed by the Neuromuscular Biomechanics Lab at Stanford University and it has been used in hundreds of biomechanical studies. The goal of the OpenSim musculoskeletal simulation is to take experimental movement data to drive the entire motion using muscle-tendon actuators. This research study used OpenSim for simulating human walking on an instrumented treadmill as it is definitely recognised as highly reliable in the dynamic simulation of human body movements (122).

To produce a muscle-driven simulation in OpenSim requires that four steps be executed, namely, the creation of a dynamic musculoskeletal model (scaling), the solving of an inverse kinematics problem, the application of a residual reduction algorithm (RRA) and the computed muscle control (CMC) (122).

1. Scaling is typically performed by comparing experimental marker data with virtual markers placed on the model.

2. Inverse kinematics helps to minimise the difference between the experimental data and the position of the model. It results in well-connected segments with constrained relative motion in the walking model.

3. The application of a RRA is intended to minimise the amount of residual force. It is more dynamically consistent with the measured ground reaction force and moment.

4. The CMC produces a coordinated muscle-driven simulation towards a desired kinematic trajectory for each participant. Several studies (17,40,55,102,105,127) utilised the OpenSim software to calculate muscle dynamics, such as muscle activities (40,102), muscle force (105), muscle fibre length (50), and joint kinetics (40,55,102,128).

2.6 Conclusion

Broadly, the literature survey provides the evidence that BW is an effective functional exercise in rehabilitation for neuro-musculoskeletal related gait impairment problems. Clinical outcomes were reported for FW and BW on a level surface, on a treadmill, and in water. Biomechanical characteristics such as the kinetic and kinematic parameters of walking were studied to understand and predict the clinical benefits which include reduction of pain, improvement in functional ability and muscle strength. The biomechanical characteristics of FW were studied extensively with respect to speed, inclination, and surface. Whereas, limited reports on BW training were found in the case of level and uphill walking at a comfortable/fixed speed on both the ground and a treadmill. Joint power and joint moment are two of many biomechanical parameters that were not reported for uphill and downhill BW.

It is important to study the biomechanical characteristics of BW with respect to speed and inclination to understand neural control strategies and musculoskeletal activity. This helps to evaluate the clinical worthiness of the biomechanical characteristics of BW, which is an important step before implementing such training on patients. A comparison of FW with BW in the form of a systematic review is an optimum way of determining the clinical benefits of these two directions of walking.

As no review could be found in the literature, this thesis set out to design two systematic reviews and an experimental simulation study. The one systematic review explores the clinical effectiveness of BW as a functional training measure for neuro-musculoskeletal gait impairments. Another review deals with the biomechanical characteristics of BW by comparing them with those of FW for healthy participants to understand the contribution of the direction of walking to the mitigation of neuro-musculoskeletal related gait impairments. The experimental study fills in the gaps by studying FW and BW at predetermined, controlled speed and inclinations for the same groups of participants.

CHAPTER 3 - The effectiveness of backward walking as a treatment for people with gait impairment: a systematic review and meta-analysis

Walking is an easy technique when given along with conventional rehabilitation programme to reduce neuro-musculoskeletal related gait impairments (129,130). The recent reports indicate that the incorporation of BW was more effective than FW in an exercise protocol (38). Walking backward is a more demanding locomotion task which has been prescribed to improve functional ability muscle strength and symmetry of normal gait (18). It is important for a therapist to know the disease-specific effectiveness of BW or FW as a valuable addition to conventional treatment. This chapter explores the effectiveness of BW from available outcomes through a systematic review.

This chapter is written in the form of a manuscript which is structured in accordance with the journal guidelines. The manuscript is under review in Journal of Clinical Rehabilitation.

Title of the manuscript:

Backward walking is effective and clinically worthwhile for people with neuro-musculoskeletal related gait impairments: a systematic review and meta-analysis

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Abstract

Question: What is the effectiveness of BW in the treatment of neuro-musculoskeletal related gait impairments? Design: Systematic review of randomized controlled trials. Participants who have gait impairment as a result of neuro-musculoskeletal conditions. Intervention: In this review, six types of comparison were analysed which included; BW *vs* Conventional physiotherapy treatment (CPT), BW/CPT *vs* CPT, BW/CPT *vs* Forward walking (FW)/CPT, BW/FW *vs* FW, BW *vs* FW and BW *vs* no exercise. Outcome measures: The primary outcome measures were the pain, functional disability, muscle strength, gait parameters, balance and plantar pressure. Results: Eight trials with 269 participants were included in this review. The effectiveness of BW was tested in participants with: knee osteoarthritis in four trials; stroke in three trials and diabetic peripheral neuropathy in one trial. The methodological quality of eligible trials was moderate, with a mean score of 5.25 points on the 10-point PEDro scale. Overall, BW with CPT was found to be significantly effective in knee OA with reduced pain (total SMD: -0.87), lower the functional difficulties (total SMD: -1.39) and improved muscle strength (SMD: 1.51). Conclusion: Among existing outcomes, this systematic review suggests that BW with CPT is effective and clinically worthwhile in people with knee OA. Review Registration: PROSPERO (CRD42016046344).

Keywords: Backward, Walking, Gait, Musculoskeletal, Neurological

1. Introduction

Neuro-musculoskeletal disease related gait impairments lead to walking disability and reduced quality of life (46,64). Worldwide, one in four people is suffering from neuro-musculoskeletal disease with a gait as a major limitation (14,15). The most common neuro-musculoskeletal disease osteoarthritis, low back pain, muscle insufficiency, stroke, multiple sclerosis, peripheral neuropathy and Parkinson's disease. The clinical outcomes of all neuro-musculoskeletal disease include pain, functional limitation, discomfort, muscle weakness, postural instability joint stiffness and asymmetry of the gait pattern (63,64). In addition, several studies have provided the evidence that people with neuro-musculoskeletal disease have adopted with secondary compensatory gait patterns (131–134). To alleviate these primary and secondary gait pattern need rehabilitation training. The common rehabilitation training is considered as conventional physiotherapy treatments (CPT) such as; stretching, strengthening, joint mobilisation and heat therapy were used as a clinical treatment. The studies show that the addition of backward walking (BW) significantly influences the balance and physical fitness in elderly people.

Backward walking exercise originated in ancient China and was practiced for good health (135). Walking backward is different from forward walking (FW) in a complete gait cycle. Start-end points of BW and FW are 'toe strike-toe off' and 'heel strike-heel off', respectively (41,81). During BW, propulsion in a backward direction followed by the reversal of leg movements exhibits a different muscle activation pattern than FW (23). Backward walking appears to result in more muscle activity, a greater level of energy expenditure, greater oxygen consumption and metabolic response (136). Additionally, BW also reduces the compressive force at the patella femoral joint, decreases the force absorption at the knee joint, and also reduces the impact force on contact due to reduced stride length and foot contact pattern (23). Advantages of BW include reduced ground reaction force at contact, limited range of motion at all the lower limb joints, and balance controlled training during walking (25,81).

Three previous narrative reviews (41,81,137) concluded that BW exercise was increasingly used in sports and clinical rehabilitation settings. The BW was identified for the improvement of muscle strength, aerobic fitness, flexibility of the body, and gait impairments (41,81). The current systematic review aims to study the effect of BW on the neuro-musculoskeletal related gait impairments. The search strategy identified three conditions which result in gait impairments such as osteoarthritis; stroke and diabetic peripheral neuropathy were treated effectively with BW.

The research question of this systematic review: What is the effectiveness of BW in the treatment of neuro-musculoskeletal related gait impairments?

2. Method

2.1 Identification and selection of studies

Systematic searches were conducted in MEDLINE (from 1966 to 2016), Scopus (from 1966 to 2016), PEDro (from 1929 to 2016), CINAHL (from1982 to 2016), PubMed (from 1966 to 2016) and Cochrane Library (from 1996 to 2016) for relevant studies from inception to 31st December 2016. Only studies published in English were considered. Search strategy steps are shown in Figure 1. The keywords used for the search are "walking", "backward", and "randomised" or "quasi-randomised", "controlled trials". Titles and abstracts were displayed and screened by a single reviewer in order to identify potentially relevant trials. Full-text copies of potentially relevant trials were retrieved and their reference lists were screened. Two independent reviewers (JS and KR) critically appraised the studies while a primary reviewer (TB) was consulted in cases where disagreements between the first and second reviewers could not be resolved through discussion. Where the eligibility was not clear, the full text was obtained for more detailed assessment. Studies that clearly did not meet the inclusion criteria were excluded at this point presented in Box 1.

History

Download history Clear history

Search	Add to builder	Query	Items found	Time
#12	Add	Search **((((walking) OR gait)) AND ((backward) OR retro))) AND (((randomized control trial) OR RCT) OR randomised control trial)**	32	06:41:29
#11	Add	Search **(((walking) OR gait)) AND ((backward) OR retro)**	819	06:41:20
#10	Add	Search **((randomized control trial) OR RCT) OR randomised control trial**	207700	06:40:51
#9	Add	Search **(backward) OR retro**	20504	06:40:23
#8	Add	Search **(walking) OR gait**	88346	06:40:08
#7	Add	Search **randomised control trial**	23160	06:39:50
#6	Add	Search **RCT**	12131	06:39:34
#5	Add	Search **randomized control trial**	195287	06:39:27
#4	Add	Search **backward**	14900	06:39:00
#3	Add	Search **retro**	5620	06:38:52
#2	Add	Search **gait**	43333	06:38:38
#1	Add	Search **walking**	58665	06:38:30

Figure 1 Search strategy (eg: PubMed)

Box 1. Inclusion criteria

Design
- Randomised or quasi-randomised controlled trial

Participants
- People with neuro-musculoskeletal conditions related to gait impairment (over the age of 18 years)

Intervention
- Intervention using backward walking exercise

Outcome measures
- Pain intensity and functional disability
- Measure of muscle strength and range of motion
- Measure of gait parameters
- Measure of balance
- Measure of plantar pressure

Comparison
- Backward walking with conventional physiotherapy treatment *versus* conventional physiotherapy treatment
- Backward walking *versus* conventional physiotherapy treatment
- Backward walking *versus* no exercise
- Backward walking with forward walking *versus* forward walking
- Backward walking *versus* forward walking
- Backward walking with conventional physiotherapy treatment *versus* forward walking along with conventional physiotherapy treatment

2.2 Assessment of characteristics of studies

2.2.1 Participants

Trials involving patients with neuro-musculoskeletal gait impairments who were over the age of 18 years were considered for inclusion. Age, sex, and level of disability were recorded to enable comparison of participants between trials.

2.2.2 Intervention

Studies were eligible for inclusion if they compared an intervention group (BW exercise or BW with CPT or BW with FW) to control group (received only CPT or FW or no treatment). The studies had to assess at least one primary outcomes focusing on pain, functional disability, muscle strength, gait parameters and balance.

2.2.3 Outcome measures

The assessed outcome measures were pain intensity (visual analogue scale (VAS)), numerical pain rating scale(NPRS), functional disability (Western Ontario and McMaster Universities Arthritis Index (WOMAC), Reduced WOMAC which is five components for pain and seven components for functional disability (rWOMAC)), muscle strength (medical research council

grading), range of motion (goniometer), gait parameters (stride length, step length, velocity, cadence, stance phase, swing phase and symmetry index), balance (Berg balance scale (BBS)) and plantar pressure (flatbed plantar measurement system).

2.3 Data analysis

Number of participants, mean and standard deviation were extracted by the primary reviewer. Standardised mean difference (SMD) with 95% of confidence interval and meta-analysis were conducted if a minimum of two trials were clinically homogeneous. Only SMD was reported for individual studies without estimating overall effect for clinically heterogeneous trials. The random effect models in RevMan 5.1 were used to calculate SMD for individual studies and meta-analysis (138).

2.4 Quality

The quality of all included trials was assessed using the PEDro scale (www.pedro.org.au). Critical appraisal of studies was carried out by two independent researchers, with disagreements resolved by a primary reviewer. The PEDro scale assesses the methodological quality and statistical reporting of a randomised trial against 11 individual criteria (139). One item relates to external validity, and the remaining 10 items can be tallied to give a score from 0 to 10 (140).

3. Results

3.1 Flow of studies through the review

The search strategy identified 1055 papers of which 15 papers were retrieved by the manual screening of titles, abstracts, and languages. A further seven studies were excluded based on the inclusion criteria specified in box-1. Finally, Eight (36–38,42,54,88,141,142) papers were identified and included in the present review. Figure 2 shows the trial selection process in a flow chart.

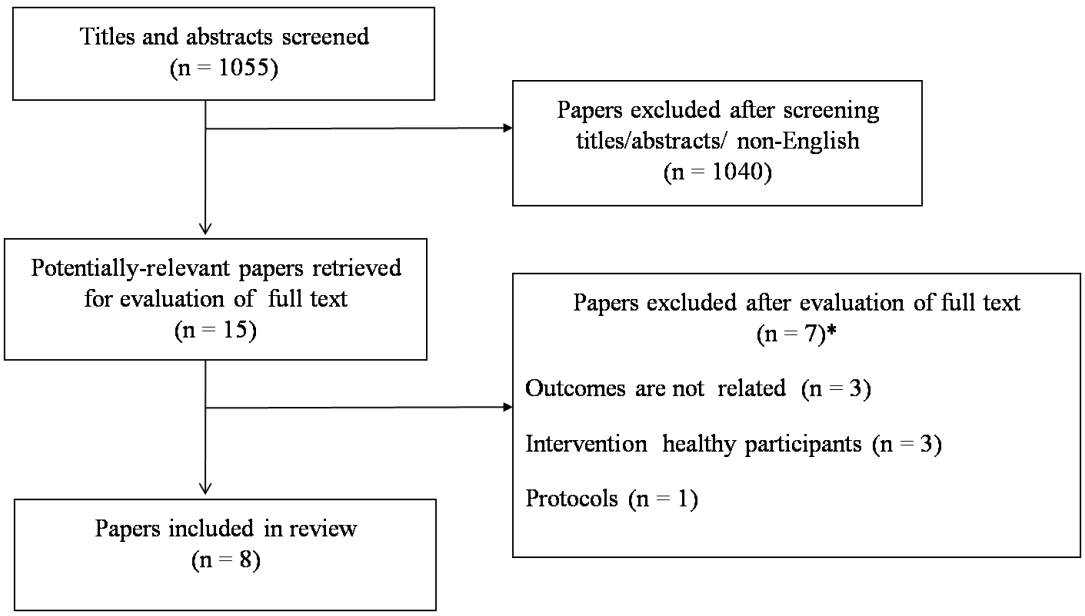


Figure 2 Flowchart - Selection of studies for inclusion in the systematic review
*Papers have been excluded for failing to meet inclusion criteria.

3.2 Characteristics of studies

The eight trials involved 269 participants were investigated for the effect of BW to improve the studied outcomes in post-intervention. The characteristics of the studies were described below and summarized in Table 1.

3.2.1 Participants

The age of the participants across the trials was ranged from 40 to 75 years. Here, 59.35% of participants were males and 40.64% females; however, two studies did not include sex as a variable. Among the eligible trials, four recruited participants were affected with knee osteoarthritis (36,37,42,142), three recruited participants who suffered a stroke (38,54,141), and one recruited participants with diabetic peripheral neuropathy(DPN) (88).

3.2.2 Intervention

Among the eligible trials, in five trials (36–38,42,88) participants walked on the ground. In the remaining three trials (54,141,142) participants walked on a treadmill with partial body weight support. The treatment periods ranged from 0 to 12 weeks. The experimental interventions included a comparison of BW *vs* CPT, BW/CPT *vs* CPT, BW *vs* FW, BW/FW *vs* FW, BW/CPT *vs* FW/CPT, BW *vs* No exercise. The reported CPT consist of one or more exercise such as, heat therapy, muscle strengthening, stretching and functional mobility (36–38,42,54,142).

3.2.3 Outcome measures

Three trials (36,37,42) reported pain using a 0 - 10 point pain scale (VAS and NPRS). Four trials reported pain with functional disability using a WOMAC (36,37,142) and rWOMAC (42). Two trials measured muscle strength, one study(36) used Medical Research Council grading to assess the concentric strength of hip abductor and hip extensor muscles. Another study (42) used the dynamometer to record quadriceps muscle strength. Only one trial used a universal goniometer to assess and report knee range of motion (ROM) (36). Three trials (38,54,141) reported for gait parameters by assessing through stride analyser (38), walking analyser (141) and stopwatch (54). One trial reported on balance using BBS (54). Finally, one trial reported plantar pressure using the flatbed plantar measurement system (88).

Table 1 Summary: characteristics of included trials (n = 8)

Study/ condition	Design	Participants	Intervention	Outcome measures
Gondhalekar et al (36)(2013) Knee OA	RCT	Exp: n = 15 (8M) Con: n = 15 (7M) mean age = 63.43 ± 6.202	Exp = BW 10min/session, 3sessions/day x 3weeks with CPT Con = CPT 20min/session, 2sessions/day x 3weeks CPT = Heat therapy and strengthening exercise.	VAS WOMAC Knee ROM Concentric strength of hip abductors and extensors, Follow-up = 3weeks
Rathi et al (42) (2014) Knee OA	RCT	Exp: n = 10, mean age 53.2 ± 5.7 Con: n = 10, mean age 53.2 ± 8.24 Sex = not mentioned	Exp = BW 10min/session, 3days/week (2weeks) with CPT 20min/day Con = CPT 20min/day CPT = Heat therapy, strengthening and stretching exercise	NPRS Reduced WOMAC Quadriceps strength Follow - up = 2 weeks
Wadhwa et al (37) (2016) Knee OA	RCT	Exp: n = 17 (7 M, 10 F) mean age 65.65 ± 4.26 Con: n = 15(6 M, 9 F) mean age 67.59 ± 4.78	Exp = BW 10 min/session, 3 weeks with CPT Con = CPT 5s hold/2s rest, 10 repetition, 3 days/week for 3 weeks CPT = Heat therapy and strengthening exercise	NPRS WOMAC TUG Follow - up = 3 weeks

Manisha et al (142) (2015) Knee OA	RCT	Exp: n = 15 Con: n = 15 Age = 40 – 60 Sex = not mentioned	Exp = BW 10 min/session, 4 weeks with CPT Con = CPT 4 weeks CPT = Heat therapy and strengthening exercise	WOMAC Step test Follow - up = 4 weeks
Kim et al (141) (2014) Stroke	RCT	Exp: n = 12 (9M), mean age 50.25 ± 16.69, Hemiplegic side (right 8) Con 1: n = 12 (8M), mean age 52.75 ± 9.21, Hemiplegic side (right 6) Con 2: n = 12 (8M), mean age 51.00 ± 14.60, Hemiplegic side (right 6)	Exp = Progressive body weight supported treadmill forward and BW training. Con 1 = Progressive body weight supported treadmill FW training Con 2 = Progressive body weight supported treadmill BW training 30min, 6 x/week (3 weeks); further 3weeks received general physiotherapy	The only measure affected side of lower extremity Walking ability Step length Stance phase Swing phase Single support Step time Symmetry index Follow – up = week 3 and 6
Takami et al (54) (2010) Stroke	RCT	Exp: n = 12 (6M), mean age 66.1 ± 6.3, Hemiplegic side (right 7) Con 1: n = 12 (9M), mean age 71.1 ± 10.6, Hemiplegic side (right 5) Con 2: n = 12 (5M), mean age 66.9 ± 10.6, Hemiplegic side (right 10)	Exp = Partial body weight supported BW training in treadmill with CPT Con 1 = CPT included with activities of daily living. Con 2 = Partial body weight supported FW training in treadmill with CPT 30min of CPT and 10 min of walking training either backward or forward; total 40 min, 6 x/week (3weeks) CPT = Functional mobility and strengthening exercise	BBS Walking speed Walk ratio Velocity Cadence Step length Follow – up = 3 weeks
Yang et al (38) (2005) Stroke	RCT	Exp: n = 13 (10M), mean age 63.38 ± 7.7, Hemiplegic side (right 8) Con: n = 12 (9M), mean age 63.42 ± 11.06, Hemiplegic side (right 8)	Exp = BW training for 30min with CPT for 40min, 3 x/week (3 weeks). Con = CPT 40min; 3 x/week (3 weeks). CPT = Functional mobility and strengthening exercise	Velocity Cadence Stride length Gait cycle Symmetry index Follow – up = 3weeks

Zhang et al (88) (2014) Diabetic peripheral neuropathy	RCT	Exp: n = 30 (16M), mean age 52.7 ± 6.5 Con: n = 30 (16M), mean age 52.7 ± 6.2	Exp = BW Con = No exercise 3 x/week (12 weeks)	Plantar pressure Follow – up = 12 weeks

M = Male, Exp = experimental group, Con = control group, BW = backward walking, CPT = conventional physiotherapy treatment, VAS = visual analogue scale, NPRS = numerical pain rating scale, WOMAC = Western Ontario and McMaster Universities Arthritis Index, ROM = range of motion, RCT = randomized controlled trial, n = number of participants, BBS = berg balance scale

3.3 Quality

The PEDro score ranged from 5 to 6 out of 10, with a mean score of 5.25 (Table 2). Due to the nature of the intervention, all the trials performed with random group allocation, baseline comparability, adequate follow-up, between-group comparison and point estimates variability. Only two studies it was stated about concealed allocation (38,54). None of the trials were clearly specified details like; intention-to-treat, the blinding procedures among the participants, assessors, and therapists.

Table 2 PEDro Scale Scores for included trials (n =8)

Study/condition	Random allocation	Concealed allocation	Baseline comparability	Blind participants	Blind therapist	Blind assessor	Adequate follow-up	Intention to treat	Between group comparison	Point estimate &variability	Total (0-10)
Gondhalekar et al (36) (2013) KneeOA	Y	N	Y	N	N	N	Y	N	Y	Y	5
Rathi et al(42) (2014) Knee OA	Y	N	Y	N	N	N	Y	N	Y	Y	5
Wadhwa et al (37) (2016) Knee OA	Y	N	Y	N	N	N	Y	N	Y	Y	5
Manisha et al (142) (2015) Knee OA	Y	N	Y	N	N	N	Y	N	Y	Y	5
Kim et al (141) (2014) Stroke	Y	N	Y	N	N	N	Y	N	Y	Y	5
Takami et al (54) (2010) Stroke	Y	Y	Y	N	N	N	N	N	Y	Y	5
Yang et al (38) (2005)Stroke	Y	Y	Y	N	N	N	Y	N	Y	Y	6
Zhang et al (88) (2014)DPN	Y	N	Y	N	N	N	Y	N	Y	Y	6

Y = yes, N = no, OA = osteoarthritis, DPN = diabetic peripheral neuropathy

3.4 Effect of intervention

The effect of the intervention was analysed from the outcomes such as pain, functional disability, muscle strength, ROM, gait parameters, balance and plantar pressure. Two outcomes (pain and functional disability) for knee OA patients were found to be homogenous in three studies. The results were pooled for metal analysis followed by standard mean difference (SMD) calculation as illustrated in Figure 3 (pain: VAS and NPRS) and Figure 4 (pain with functional disability: WOMAC). All the remaining outcomes for knee OA, stroke, and DPN were heterogeneous; hence only SMD was calculated and presented in Supplementary figure 1, 2 and 3.The summary of time point, results and conclusions are pooled in Table 3 at the end of the section.

3.4.1 Pain and functional disabilities

3.4.1.1 Pain

The effect of BW/CPT *vs* CPT on pain was examined by pooling of post-intervention data from the clinically homogeneous three trials (36,37,42) involving 82 patients with knee OA. The meta-analysis of the pain outcomes from VAS(36) and NPRS(37,42) was shown in Figure 3. The trials favored the experimental group with the total SMD of -0.87 [-1.38 to -0.36] and heterogeneity of I^2= 17% indicates overall pooled data statistically favor to the experimental groups to reduce the knee OA pain.

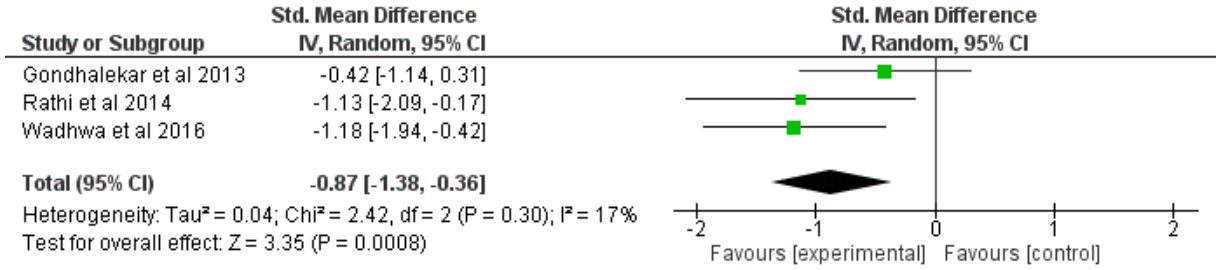


Figure 3 SMD (95% CI) calculated from the three trials for the BW/CPT *vs* CPT on pain experienced in patients with knee OA.

3.4.1.2 Pain with functional disability

The difficulties of the functional ability in BW/CPT *vs* CPT was examined by pooling of post-intervention data from four trials presented in Figure 4. It involving 132 patients with knee OA in WOMAC scale for pain with functional disability (36,37,42,142). The overall effect shows the statistically significant reduction of WOMAC parameters -1.39 [-2.06 to -0.72]. Though the

data show a heterogeneity of I^2 = 65%the statistically significant effect of the outcomes favors experimental groups.

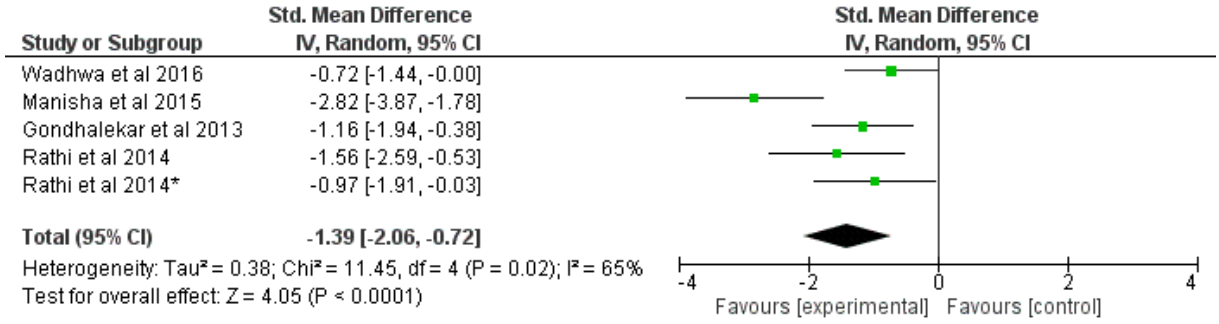


Figure 4 SMD (95% CI) calculated from the three trials for the BW/CPT on WOMAC experienced in patients with knee osteoarthritis.

*pain

3.4.2 Strength, ROM, gait parameters, balance and plantar pressure

All these outcomes were heterogeneous hence only SMD was reported in the forest plot.

3.4.2.1 Strength and ROM

Only one trial (42) reported the quadriceps muscle strength, involving 20 patients with knee OA. While another trial (36) reported the hip abductors muscle strength, hip extensors muscle strength and knee joint ROM involving 30 participants. The effect of muscle strength and ROM for BW/CPT *vs* CPT was examined by SMD from the post-intervention data. The calculated SMD value for quadriceps muscle strength 1.51 [0.49 to 2.53], hip abductors muscle strength 0.60 [-0.13 to 1.34], hip extensor muscle strength 1.11 [0.34 to 1.89] and knee ROM 1.66 [0.81 to 2.50] were listed in Supplementary figure 1. This SMD value of muscle strength and knee ROM showed significant improvement compared to CPT. The remaining six included trials did not measure strength and ROM.

3.4.2.2 Gait parameters

Three trials (38,54,141) reported the gait parameters, involving 97 patients with stroke. Kim et al.,(141) and Takami et al.,(54) categorized the stroke patients into three groups (Table 2). In the present analysis, to compare the effect of BW, the SMD value were calculated for the chosen experimental *vs* control groups as given in Supplementary figure 2. The SMD results ascertained the improvement of the experimental group from '+' ve value of step length, stride length, velocity, cadence, stance phase, swing phase and symmetry index and '-'ve value of step time. Among the three trials; ground (38) and treadmill (54,141) were used as walking surfaces.

Walking on a treadmill with partial body weight support was studied in two trials (54,141). In the comparison of BW/FW *vs* FW, improvements were observed from the significant differences of step time -0.80 [-1.64 to 0.03] at the 3rd and 6thweek. Other parameters did not show any further improvements. In the BW/CPT *vs* CPT, the participants BW on treadmill shows significant improvements were observed in the temporal variables; velocity 0.89 [-0.00 to 1.77] and step length 0.89 [0.00 to 1.78]. In the BW/CPT *vs* CPT, the analysis of the trial based on BW on the ground shows significant improvement, only in stride length 1.06 [0.21 to 1.91]. It is noted that BW on the treadmill at BW *vs* FW and BW/CPT *vs* FW/CPT does not affect the gait variables. The remaining five trials did not measure the gait parameters.

3.4.2.3 Balance

One study (54) reported the balance of patients with stroke using BBS after three weeks of the treatment. To know the effect of BW, two sets of comparison were made through the SMD method (Supplementary figure 2). The calculated SMD value for BW/CPT *vs* CPT and BW/CPT *vs* FW/CPT are 0.92 [0.03 to 1.81] and 0.93 [-0.00 to 1.87] respectively. These values indicate significant balance improvement in patients with stroke in both comparisons than CPT alone.

3.4.2.4 Plantar pressure

One study (88) measured the distribution of plantar pressure in 60 DPN patients for 12 weeks of follow up. The SMD value in Supplementary figure 3 show the significant reduction in MT 1 -0.82 and -1.51 [-2.09 to -0.93], MT 3 -0.94 [-1.48 to -0.41] and -0.93 [-1.46 to -0.40] right and left, MT 2 -1.24 [-1.80 to -0.68] left and heel medial -0.53 [-1.04 to -0.01] left compared to no exercise. Other foot pressure points show significantly not effective at 95% CI.

Table 3 Results and conclusion of studies for effect of intervention (n = 8)

Intervention	Study and condition	Time point	Results	Conclusions
Pain	Gondhalekar et al (36) (2013) Knee OA	At completion of 3weeks of the treatment	Pain (0-10): SMD -0.42 (95% CI –1.14 to 0.31) in favor of BW with CPT	*Author:* BW/CPT no significant reduction in pain compared to CPT *Review*: BW/CPT reduced pain compared to CPT. The study had moderate methodological quality and low risk of bias
	Rathi et al (42) (2014) Knee OA	At completion of 2 weeks of the treatment	Pain (0-10): SMD -1.13 (95% CI –2.09 to -0.17) in favor of BW with CPT	*Authors:* BW/CPT significantly reduced pain compared to CPT *Review*: BW/CPT significantly reduced pain compared to CPT. The study had moderate methodological quality and low risk of bias
	Wadhwa et al (37) (2016) Knee OA	At completion of 3weeks of the treatment	Pain (0-10): SMD -1.18 (95% CI –1.94 to -0.42) in favor of BW with CPT	
Pain with Functional disability	Gondhalekaret al (36) (2013) Knee OA	At completion of 3weeks of the treatment	Pain with FD: SMD -1.16 (95% CI –1.94 to -0.38) in favor of BW with CPT	*Author:* BW/CPT significant improvement in pain with functional disability compared to CPT *Review*: BW/CPT significant improvement in pain with functional disability compared to CPT. The study had moderate methodological quality
	Rathi et al (42) (2014) Knee OA	At completion of 2 weeks of the treatment	Pain: SMD -0.97 (95% CI –1.91 to -0.03) in favor of BW with CPT FD: SMD -1.56 (95% CI –2.59 to -0.53) in favor of BW with CPT	
	Wadhwa et al (37) (2016) Knee OA	At completion of 3 weeks of the treatment	Pain with FD: SMD -0.72 (95% CI –1.46 to -0.02) in favor of BW with CPT	

	Manisha et al (142) (2015) Knee OA	At completion of 4 weeks of the treatment	Pain with FD: SMD -3.24 (95% CI –4.37 to -2.10) in favor of BW with CPT	
Strength and ROM	Gondhalekar et al (36) (2013) Knee OA	At completion of 3weeks of the treatment	Hip abductors: SMD 0.60 (95% CI –0.13 to 1.34) in favor of CPT Hip extensors: SMD 1.11 (95% CI 0.34 to 1.89) in favor of CPT Knee ROM: SMD 1.66 (95% CI 0.81 to 2.50) in favor of CPT	*Author:* BW/CPT did not show significant improvement in muscle strength and ROM compared to CPT *Review*: BW/CPT show significant improvement in muscle strength and ROM compared to CPT. The study had moderate methodological quality and low risk of bias.
	Rathi et al(42) (2014) Knee OA	At completion of 2 weeks of the treatment	Muscle strength: Quadriceps: SMD 1.51 (95% CI 0.49 to 2.53) in favor of BW with CPT	*Author:* BW/CPT showed significant improvement in muscle strength compared to CPT *Review*: BW/CPT significant improvement in muscle strength compared to CPT. The study had moderate methodological quality and low risk of bias.
Gait parameters	Kim et al (141) (2014) Stroke	At completion of 6 weeks of the treatment	Step length: SMD 0.53 (95% CI -0.29 to 1.35) in favor of BW with FW Stance phase: SMD 0.03 (95% CI -0.77 to 0.83) in favor of BW with FW Swing phase: SMD -0.06 (95% CI -0.86 to 0.74) in favor of BW with FW Single support: SMD 0.30 (95% CI -0.51 to 1.10) in favor of BW with FW Step time: SMD -0.85 (95% CI -1.70 to -0.01) in favor of BW with FW Symmetry index: SMD 0.26 (95% CI -0.55 to 1.06) in favor of BW with FW	*Author:* BW/FW showed significant improvement in all specified gait parameters 3weeks after the treatment. While follow up of 6th week showed only significant improvement in step length compared to FW *Review*: BW/FW showed significant improvement in gait parameters compared to FW. The study had moderate methodological quality and moderate risk of bias.

	Takami et al (54) (2010) Stroke	At completion of 3 weeks of the treatment	Velocity: SMD 0.89 (95% CI -0.00 to 1.77) in favor of BW with CPT Cadence: SMD 0.59 (95% CI -0.27 to 1.45) in favor of BW with CPT Step length: SMD 0.89 (95% CI 0.00 to 1.78) in favor of BW with CPT	*Author:* BW/CPT showed significant improvement in all specified gait parameters 3weeks after the treatment *Review*: BW/CPT showed significant improvement in gait parameters compared to CPT. The study had moderate methodological quality and low risk of bias.
	Yang et al (38) (2005) Stroke	At completion of 3 weeks of the treatment	Velocity: SMD 0.31 (95% CI -0.48 to 1.10) in favor of BW with CPT Cadence: SMD -0.18 (95% CI -0.96 to 0.61) in favor of BW with CPT Stride length: SMD 1.06 (95% CI 0.21 to 1.91) in favor of BW with CPT Gait cycle: SMD -0.16 (95% CI -0.94 to 0.63) in favor of BW with CPT Symmetry index: SMD 0.34 (95% CI -0.45 to 1.13) in favor of BW with CPT	*Author:* BW/CPT showed significant improvement in all specified gait parameters except cadence and gait cycle *Review*: BW/CPT showed significant improvement in gait parameters compared to CPT. The study had high methodological quality and low risk of bias.
Balance	Takami et al (54) (2010) Stroke	At completion of 3 weeks of the treatment	BBS: SMD 0.92 (95% CI 0.03 to 1.81), 0.93 (95% CI -0.00 to 1.87) in favor of BW with CPT	*Author:* BW/CPT showed no significant improvement in balance compared to CPT. But showed significant improvement in within group *Review*: BW/CPT showed significant improvement in balance. The study had moderate methodological quality and low risk of bias.

Plantar pressure	Zhang et al (88) (2014) Diabetic peripheral neuropathy	At completion of 12weeks of the treatment	Peak plantar pressure left and right MT 1: SMD -1.51 (95% CI -2.09 to -0.93)& -0.82 (95% CI -1.35 to 0.30) in favor of BW MT 2: SMD -1.24 (95% CI -1.80 to -0.68)& -0.02 (95% CI -0.53 to 0.48) in favor of BW MT 3: SMD -0.93 (95% CI -1.46 to -0.40)& -0.94 (95% CI -1.48 to 0.41) in favor of BW Mid foot: SMD 0.49 (95% CI -0.02 to 1.01)& -0.19 (95% CI -0.70 to 0.31) in favor of BW Heel medial: SMD -0.53 (95% CI -1.04 to -0.01)& -0.21 (95% CI -0.72 to 0.30) in favor of BW	*Author:* Even distribution of the plantar pressure in the experimental group. *Review*: The reduction in peak pressure improves the possibility of balance and reduces foot ulcers. The study had high methodological quality and low risk of bias.

a – "Author" refers to the conclusion of the author(s) of the specific paper, while "Review" refers to the conclusions of this systematic review. BW = backward walking, CPT = conventional physiotherapy treatment, OA = osteoarthritis, FD = functional disability, ROM = range of motion, BBS = berg balance scale, MT = metatarsal, SMD = standardised mean difference.

4. Discussion

The present systematic review provides evidence that BW significantly improves the mentioned outcome related to neuro-musculoskeletal related gait impairments. The identified eight trials show BW exercises were included in the clinical rehabilitation of knee OA, stroke and DPN. Here, six comparison were reported with BW *vs* CPT, BW/CPT *vs* CPT, BW *vs* FW, BW/FW *vs* FW, BW/CPT *vs* FW/CPT, BW *vs* No exercise. Among these six comparison, BW/CPT *vs* CPT was analysed in six trials (36–38,42,54,142) which included outcome measure such as, pain, functional disability, muscle strength, ROM, and gait parameters. The clinical homogeneity of the three trials made it possible to perform meta-analysis for the pain and functional disability variables. The pooled data indicate that BW combined with CPT resulted in significant reduction of knee OA pain compared to CPT alone (-0.87 [-1.38 to -0.36] and heterogeneity of I^2= 17%). The effective pain relief achieved in BW with CPT can be attributed to reduced adductor moment at the knee joint and decreased compressive forces in the medial compartment of the knee (21,25). Apart from pain and functional disability, other outcomes were analysed through standard mean deviation (SMD) method due to their clinical heterogeneity.

The improvement of functional ability in BW with CPT may be attributed to the reduction of pain and increased muscle activation patterns (38,143). The comparison of muscle strength calculated through SMD method shows significant activation of lower limb muscle during BW. The improved muscle strength of hip extensors leads to reduced hip flexion moment and increased quadriceps function (82,105). This prevents abnormal loading of the knee, reduces compression force in the patella femoral joint and decreases force absorption at the knee joint (21,144).

Another two trials studied spatial and temporal parameters for patients with stroke. The comparison (BW/CPT *vs* CPT) indicates the significant increase of step length (0.89), cadence (0.59) and velocity (0.89) in treadmill walking but ground walking shows only stride length (1.06) improvement. The improved gait parameters are due to isolated movement of the knee alternating flexion and extension during BW (25,54,141).

The comparison of BW and FW was studied in one trial for patients with stroke (141). The SMD analysis shows the non-significant improvement in gait parameters. In the same trial, BW/FW *vs* FW showed improvement in SMD value for step length and step time. The activation of flexors and extensors of lower limbs would elicit higher center of gravity which would improve the step length (141). Backward walking on a treadmill with partial body weight support reduces foot-dragging during the swing phase and thus results in decreased step time.

The other comparison of BW/CPT *vs* FW/CPT and BW/CPT *vs* CPT show significant improvement in balance from the higher ground contact time and motor control ability. Backward walking *vs* no exercise was studied in one trial for the plantar pressure in patients with DPN (88). The SMD calculation shows that the peak plantar pressure in the forefoot dropped significantly and the midfoot pressure was slightly increased. Thus, the plantar pressure would be distributed in a much wider range across the whole foot area. It help to prevent the foot ulcer in DPN patients during BW than no exercise (54,88). Above mentioned parameters are statistically significant and clinically worthwhile. Clinically, BW is an easy intervention to implement and it is inexpensive, but the beginning of BW training required close professional supervision for safety. Backward walking can also be added to different walking interventions (e.g., dual task, cueing and virtual illusion in front of a treadmill) and may thereby increase the effect of an intervention.

The strength of this systematic review lies in the use of a highly sensitive search strategy to identify trials in all major databases, citation tracking, and manual reference list checks. The strict inclusion criteria were used to include only randomized or quasi-randomized control trials as they are less bias than other designs (145).

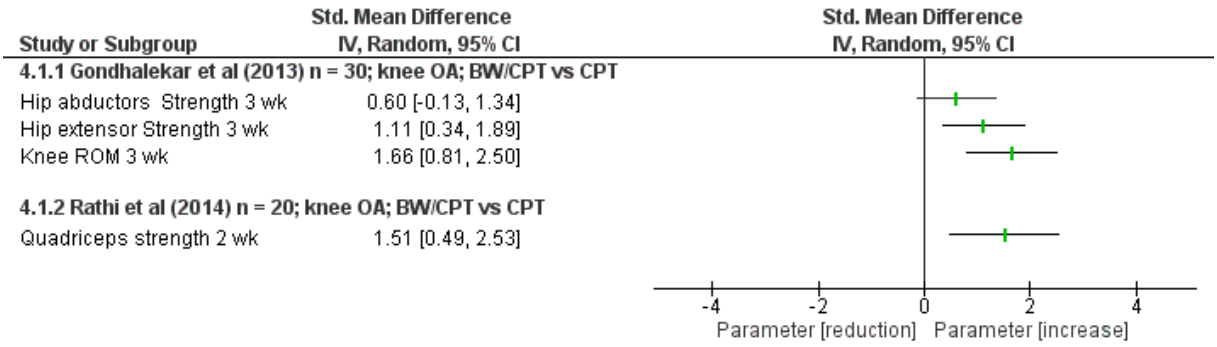
A limitation of this systematic review is that only two meta-analyses could be performed from the available homogeneous data. No other meta-analysis was conducted due to clinical heterogeneity and lack of common outcome among the included trials. The CPT consists of a different set of exercise. The small sample sizes and lack of blinding reduce the reliability and validity of the outcome. Further research is needed to reduce the statistical uncertainties for designing the BW combinations as an exercise program.

In conclusion, this systematic review suggests that BW with CPT is clinically worthwhile for the patients with neuro-musculoskeletal related gait impairments. The effect of BW was found to be statistically significant for pain, functional disabilities and thigh muscles in knee OA participants, gait parameters and balance in stroke participants, and plantar pressure in DPN participants. However, the review is based on a number of moderate studies; we recommend that BW exercise should be implemented into clinical practice as a therapy for diseases which result in gait impairments and a variety of knee problems, particularly when the aim is to improve functional ability and muscle strength.

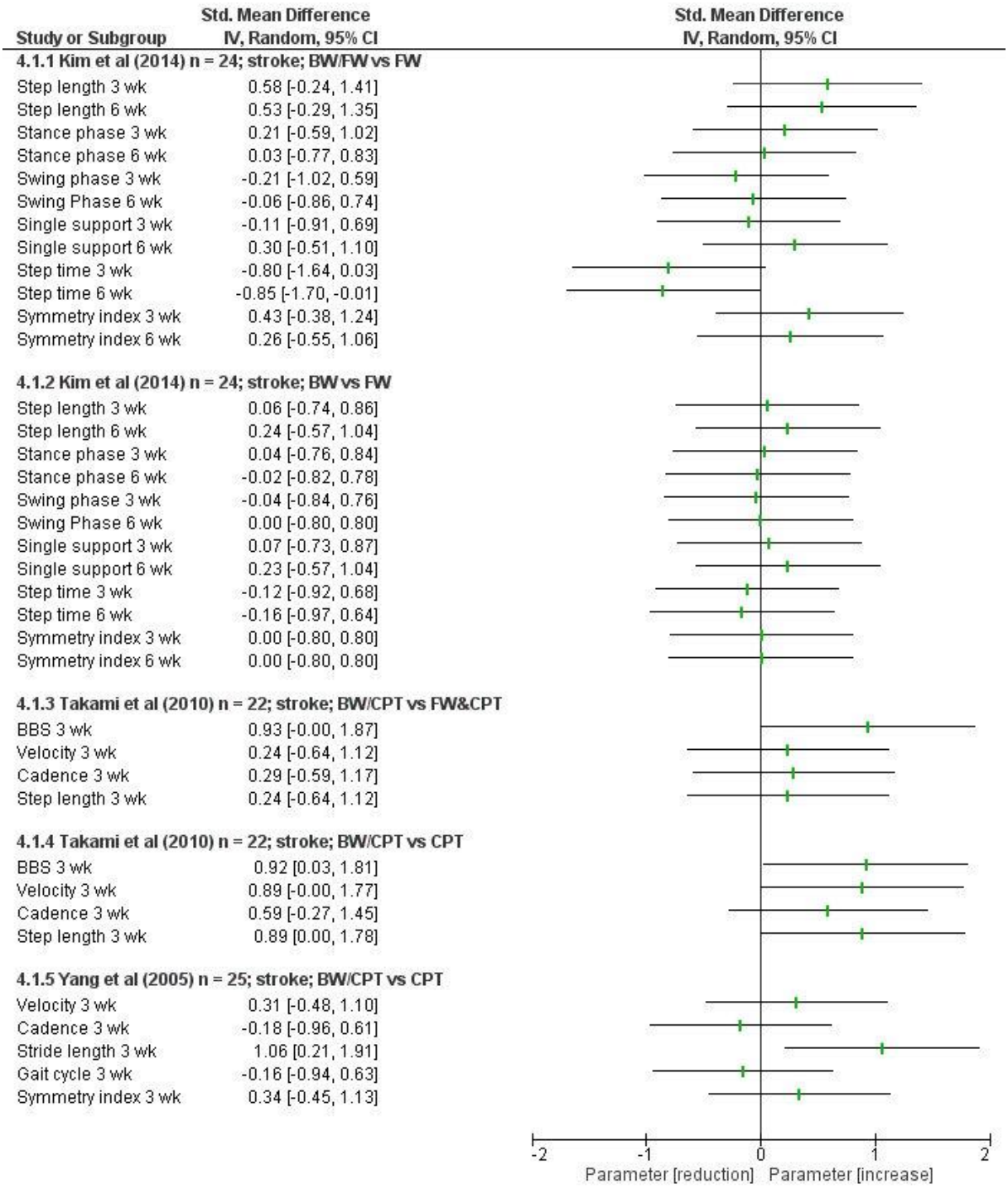
5. Highlights

- Statistical effectiveness of BW reviewed systematically
- BW exercise implemented for the clinical outcomes of knee OA, stroke and DPN
- BW with CPT reduces pain, improves functional ability and increases quadriceps strength

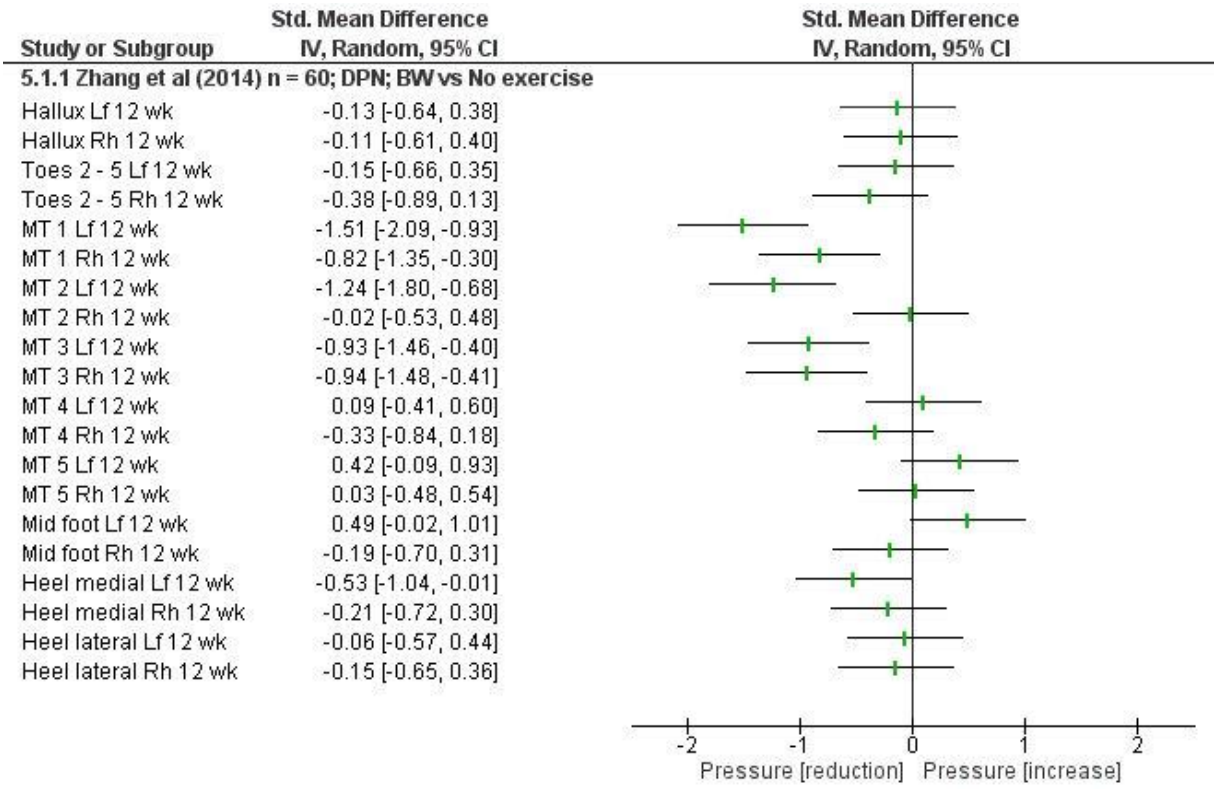
6. Supplementary material



Supplementary figure 1 SMD (95% CI) calculated from the two trials for the BW/CPT on strength and ROM experienced in patients with knee OA.



Supplementary figure 2 SMD (95% CI) calculated from the three trials for four types of comparison on gait parameters and balance experienced in patients with stroke.



Supplementary figure 3 SMD (95% CI) calculated from the two trials for the BW *vs* No exercise on the distribution of plantar pressure in patients with DPN.

MT = Meta tarsal, Lf= left, Rh = right

CHAPTER 4 -The comparison of biomechanical characteristics of backward and forward walking: A systematic review

In the previous chapter, BW in the treatment of neuro-musculoskeletal related gait impairments was found to be effective. Although BW kinetic parameter can be considered as not a mirror image of FW, BW's unique biomechanical characteristics enhanced its effectiveness (26,39,81,82). The clinical importance of BW led us to study the kinematic and kinetic outcomes of the walking from existing literature. This chapter systematically review the biomechanical difference between BW and FW. Quantitative and descriptive analyses were given according to the available data.

This chapter is written in the form of the manuscript which is structured in accordance with journal guidelines. The manuscript is under review in Gait &Posture journal.

Title of the manuscript:

The comparison of biomechanical characteristics of backward and forward walking: A systematic review

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Abstract

Background: Backward walking (BW) is increasingly used in musculoskeletal and neurological rehabilitation. However no systematic reviews exist on the comparison of biomechanical characteristics of BW with that of forward walking (FW). **Objective**: To identify the difference between FW and BW through systematic review of kinematic and kinetic analysis. **Methods:** The reviewers identified relevant studies in electronic databases such as MEDLINE, Scopus, PEDro, CINAHL, PubMed and the Cochrane library. Inclusion criteria were observational studies involving BW compared to FW in healthy adults. **Results:** Twenty BW studies with 244 participants were identified. The kinetic, kinematic, muscle activity, ground reaction force (GRF) and gait parameters from BW and FW were compared by standard mean difference (SMD) value. In cases where SMD analysis was not possible, the outcomes were compared by relevant description. Irrespective of environments, the biomechanical outcomes of BW were found to be significantly different from FW. During BW, hip flexion, knee flexion, tibiofemoral joint reaction force, ankle joint power, hip joint power, GRF, step length, stride length and walking speed were lower. During BW most of the muscles changed their pattern of higher activity. **Conclusion:** The review concludes the BW is significantly different from FW in terms of biomechanical characteristics such as reduced range of motion, increased muscle activity, reduced GRF and differing gait parameters. Hence, the modified neural control strategies were required to produce BW from FW.

Keyword: Walking, Gait, Backward, Biomechanics

1. Introduction

Walking is a popular form of physical activity that improves quality of life (146). Broadly, human walking can be classified into three types: forward walking (FW), backward walking (BW) and lateral walking (147). Biomechanically, the motion of a lower limb is considered as a double pendulum to extract the kinetic and kinematic parameters of the joints (148). In this regard, BW cannot be considered as a simple time reversal technique of FW (40,41). In daily practice, humans have adapted to FW due to the advantage of the visual cues. The asymmetric nature of the human anatomy allows for significant differences in knee angle, ankle angle and ankle muscle activity (23,40,41). Though FW and BW are controlled by a common neural circuitry, BW requires additional control from supraspinal source (25,39,94).

The kinematics and kinetics of BW and FW were studied in various environmental conditions with controlled parameters. The conditions were broadly classified as treadmill, ground and in water walking with systematic changes in speed and visual cues (25,98,105,149,150). These methods were linked to the changes in gait parameters, joint angles, joint forces and muscle activity patterns. Over the years, many technical tools have been developed to access the biomechanical variables in walking (17). The traditional analysis tools included goniometry, accelerometer, electromyography (EMG), resistive grid walkway, foot switches, force plate and treadmill with video analysis (82,136,151). In modern days, sophisticated instruments are adapted to capture 2D or 3D kinematic gait patterns in movement analysis laboratories. The unique combinations of the traditional and modern instruments are interfaced with computer technology. Synchronized high-speed cameras were used to capture anatomically placed reflective markers with advanced software applications for motion analysis (52,92,130).

The analysis of simultaneous data from joint motion along with EMG contributes to the understanding of the walking patterns and muscle activities. Biomechanically, toe strike and heel strike are considered as the initial contact for BW and FW, respectively (84). The kinematics, especially knee joint flexion range of movement, is less in BW due to the difference in movement trajectories (23,25,40). There are less hip, knee, and ankle joint power generation during BW than FW. During BW ankle joint power generation is less than hip and knee power. These kinetic and kinematic indices illustrate the plantar flexion plays only a small role in propulsion, and the propulsive force in BW may come from other segments than the ankle (23,152,153). Furthermore, EMG studies of BW shown rectus femoris, gluteus maximus, and lateral gastrocnemius had greater muscle activity in comparison to FW (25,38). There are distinct benefits of BW than FW (98,136). Backward walking is advantageous for both fitness

training and rehabilitation like increased core muscle activity, improved balance and motor control ability (38,54).

The authors found three narrative reviews of BW and FW literature (41,47,81). These reviews focus on basic neural circuits and rehabilitation of various medical conditions. The current systematic review aimed to investigate the difference in biomechanical characteristics of BW and FW by comparing gait parameters, muscle activity, kinetic and kinematic factors during treadmill, ground and in water walking.

2. Methods

The methods followed in this systematic review are aligned with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (154). It satisfies 21 items in the PRISMA checklist which were presented in Supplementary table-1.

2.1 Eligibility criteria

Observational studies which compared BW with FW in healthy adult participants between the ages of 18 to 40 years young adulthood were considered for inclusion. Studies were included if they used any of the following outcome measures: kinematics, kinetics, muscle activity, ground reaction force and gait parameters.

2.2 Information sources and search strategy

The search strategies were designed to find both published and unpublished studies in all languages and time periods for inclusion. The following databases were used to search for studies published from inception until 31 December 2016: MEDLINE (from 1966 to 2016), Scopus (from 1966 to 2016), PEDro (from 1929 to 2016), CINAHL (from1982 to 2016), Cochrane library (from 1996 to 2016) and PubMed (from 1966 to 2016) Searches were performed in ‘all fields’ and the filter function ‘humans’ was applied where possible.

A three-step search strategy was utilized in this review. An initial search was undertaken in MEDLINE using the keywords “backward” and “walking”. This step helped to identify the additional keywords contained in the title, abstract and index terms used in the articles. The relevant keywords found for the study were ‘walking’, ‘gait’, ‘retro’ and ‘backward’ (Supplementary figure-1). The second search within all databases was undertaken using identified keywords. Thirdly, the reference lists of all identified full-text papers were reviewed for further potential titles. The reviewers contacted the authors or journal editors for their unpublished referenced trials and where the full texts were not available online.

2.3 Study selection

The titles, abstracts and full texts (as relevant) were reviewed against the inclusion criteria. Two independent reviewers (JS and KR) critically appraised the studies while a primary reviewer (TB) was consulted in cases where disagreements between the first and second reviewers could not be resolved through discussion.

2.4 Data collection process

Two reviewers extracted data by using the standardized data extraction tool from the Joanna Briggs Institute (JBI)-MAStARI) (155). Study characteristics, participant demographic data, methods and tools were summarized and presented in the table format (Table-1). Summary of data for each study, including mean and standard deviation was extracted independently by a primary reviewer. Due to the clinical heterogeneity of the studies included in this systematic review a meta-analysis was not possible. Therefore, only standardised mean differences (SMD) were calculated to define the effect sizes from existing data. The SMD analysis was performed using the RevMan version 5.1 (138). Among the 20 trials, sufficient data in the form of mean and standard deviation were available for eight trials to calculate SMD value. The remaining 12 trials were discussed by the descriptive method.

2.5 Risk of bias in included studies

Two assessment tools were used to review the risk of bias in the included studies: 1. Quality assessment using the JBI-MAStARI (Table-2)(155), 2. The evaluation of the biomechanical methods by quality assessment tool (Table-3) (156,157). Two authors independently evaluated the quality of the included studies using JBI risk of bias tool and the modified methodological assessment of kinematic, kinetic and EMG gait analysis tool described in Supplementary table-2. This risk of bias was classified as follows: high risk of bias, low risk of bias and unclear risk of bias. These grades were identified through discussions between the two reviewers.

3. Results

3.1 Study selection

A total of 1895 records were found from databases and other sources. After removing duplicates and inappropriate studies based on titles and abstracts, the full texts of 56 studies were retrieved. A further, 36 studies were excluded based on the outcome measures used. Twenty trials were identified and included in the review. Among these 20 trials, the available one non-English trial

(Japanese) translated through Google translate and discussed with a native Japanese speaker. The selection procedure is shown in flow diagram Figure-1.

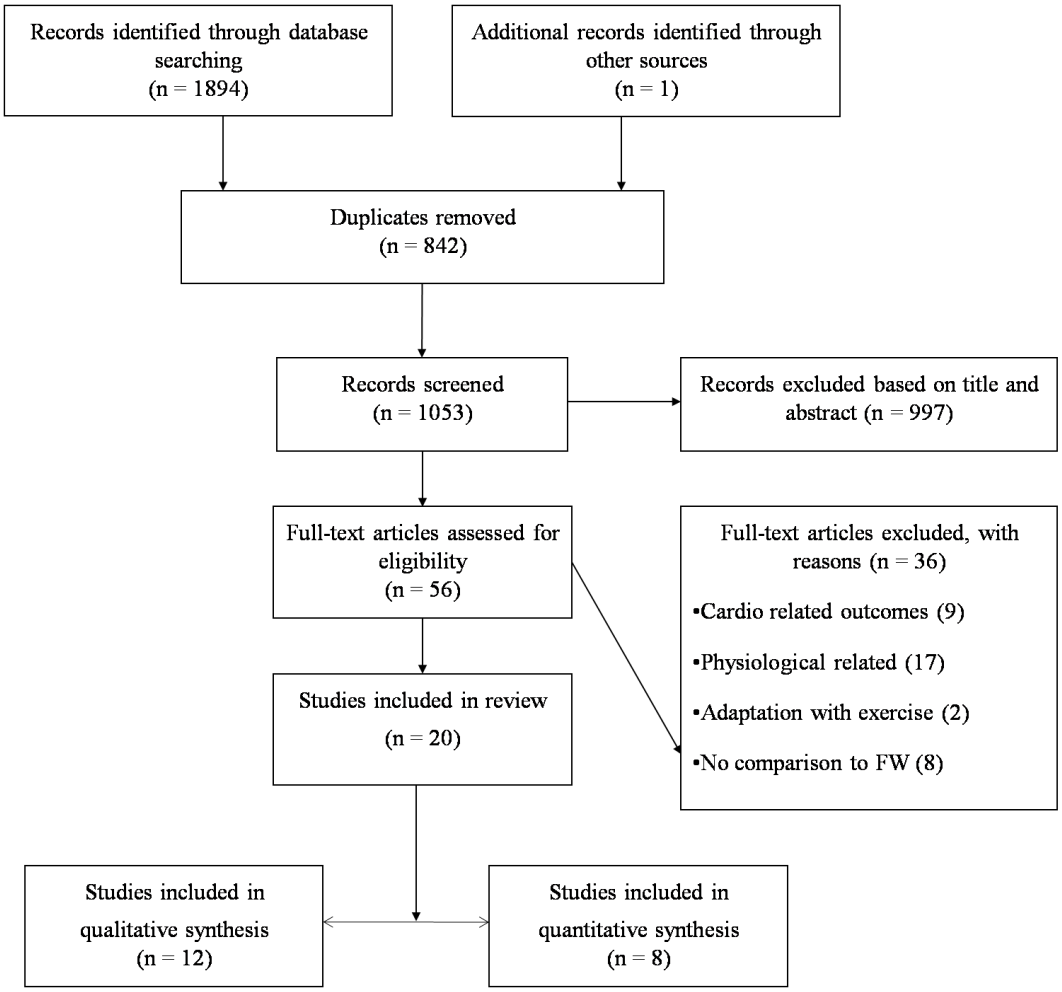


Figure -1 The flow chart represents the extraction process followed to select the inclusion studies.

3.2 Study characteristics

For all included studies, anthropometric measurements of the participants, exposure variables, and outcome measures were considered as described below and also mentioned in Table-1.

3.2.1 Anthropometric measurements

A minimum age of 18 years was one of the inclusion criteria for this review. Nineteen out of 20 selected studies reported the age range between 20 to 40 of the participants, the remaining one study used the term ‘adult’ without specifications of their participants’ ages (95). Eleven studies reported their participants’ mean age, mean height and mean weight. Only three studies reported the BMI (< 30) (110,149,150).

3.2.2 Exposure variables

The exposure variables of the 20 included studies were evaluated with different environmental factors and conditions. The walking environments were treadmill (9 studies), ground (8 studies) and walking in water (3 studies) as listed in Table-1. The walking conditions include the changes of visual cues, treadmill speed, in water with or without current and hard or foam rubber surfaces. These variables led to changes in results of outcome measures.

Table - 1 Summary of included study characteristics

No	Author-year	Population	Methods	Tools
1.	Błażkiewicz et al.[2013]	N= 1m Age = 22y Height = 185cm Weight = 80kg	The participant was walking along a 10m walkway with self-selected velocity. Recorded 1 static trial and 1 FW and BW trial.	Kinematic = Vicon software, Plug in gait Force plate = 1000HZ kistler plate EMG= 1000HZ wireless Noraxon, low and high pass filter, butter worth filter. Muscles = TA,RF,TP,BF,GM and Iliacus Simulation = Opensim, 19DOF, 92 hill type model.
2.	Hidefumi et al [2013]	N= 12 Age= 21.8(2.2)y Height = 172.5 (5.9)cm Weight = 58.8(4.6) kg BMI= 22.4(1.2)	Participants were instructed to walk FW and BW at different speed 20m/min, 40m/min, 60m/min and 80m/min. Then 3 minutes' rest for each walking speed.	Kinematic = treadmill EMG = surface EMG deriving at bipolar lead, 10 Hz highpass filter Muscles = VM, RF, GAS L, TA, SOL, GM, G MED, BF Other = foot switches Analysis = left limb
3.	Lee et al. [2013]	N= 31 [26m, 5f] Age= 22.4(3.2)y Height = 171.5(5.5)cm Weight = 70(10.4)kg	Participant performed 10 FW trials and 40 BW trials on a 10-m walkway with bare feet.	Kinematic = Vicon, plug in gait Force plate = 2 Kistler and 2 AMTI 1080HZ Simulation = biomechanical modeller pipeline.
4.	Naoki Soda et al. [2013]	N= 11 [7m, 4f] Age=23.8(4.6)y Height = 167.5(8.5)cm Weight = 59.9(12.6)kg	Participants performed FW and BW. 3 trials were analysed	Kinematic = Vicon nexus, 6camers 100HZ, plug in gait Force plate = 3, 1000HZ force plate
5.	Bolton et al. [2012]	N= 10 [5m,5f] Age= 21-36y	The participants were given the choice to either first do FW or BW.	Kinematic = electro goniometer placed in right knee and ankle Force plate = force sensitive resistance in participant shoes

			While walking on treadmill 20 perturbations were applied to participant's waist at each point of the step cycle. Each trace is the average of 9 trials	EMG = full wave rectifier and low pass filter, butter worth filter. Muscles =SOL,TA,VL and ST Analysis = only in the right leg.
6.	Jansen et al. [2012]	N= 10 [6m,4f] Age= 26.1(4.3)y	Participant walked FW and BW at a speed of 4 km/h	Kinematic = 100HZ krypton cameras Force plate = integrated into to the split-belt treadmill at 1000HZ EMG = wireless 1000HZ Muscles = TA,GAS L,SOL,VL,RF,BF and ST Simulation = OpenSim, 27DOF, 92 hill type model.
7.	Zonthichai et al. [2012]	N= 54m Age= 20-39y BMI= >30	Participants performed both FW and BW. Walking speed started with 0.8m/s and was stepped up to 1.0, 1.2, 1.4 and 1.6m/s every minute.	Kinematic = split-belt treadmill, 6 cameras and 1 digital video camera, qualisys track manager software. Force plate = Bertec inbuilt 2 FP 100Hz. Others = inverse dynamic
8.	Carneiro et al. [2010]	N= 22 [11m,11f] Mean Age= 24.6(2.6)y Mean Height= 1.71(0.79)m. Mean Weight = 66.8(11.2)kg	2 trials of walking The participant was walked along a 7.5m walkway with 2 environments and 2 directions [FW and BW, land and in water] 10 trials were performed for each condition, the total of 40 trials was recorded.	Kinematic = sanyoxacti 30HZ Force Plate = extensometric plate
9.	Jansen et al. [2010]	N= 1m Age= 28y	Participant walked FW and BW at a speed of 4 km/h	Kinematic = 100HZ krypton cameras Force plate = integrated with to the split-belt treadmill at 1000HZ EMG = wireless 1000HZ Muscles = TA,GAS L,SOL,VL,RF,BF and ST Simulation = OpenSim, 19 DOF, 92 hill type model.
10.	Katsavelis et al. [2010]	N= 6 [4m, 2f] Age= 27.7(2)y Height = 175.3(10)cm Weight = 68.7(11)kg	Participants walked on treadmill with 4 conditions 1. BW with no optic flow (OF) 2.BW with OF 3. BW with OF backward 4. FW with OF	Kinematic = EVART software, 8 cameras 60HZ, reflective markers, motorized treadmill.

11.	Maeda et al. [2010]	N= 5f Age= 21.6(0.9)y Height = 156.4(5.4)m Weight = 48.1(7.9)kg	Participant performed FW, BW LW and laboured walking on land 5m, and in water 2m.	EMG = Noraxonmyosystem Muscles = GMED, BFlh, TA, GAS M, adducent muscle group hip joint and medial great muscle.
12.	Nunzio et al. [2009]	N= 10 [6m, 4f] Age= 30.4(10.5)y Height = 171.8(6.8)cm Weight = 67.7(9.3)kg Foot length= 25(1.7)cm	Participants performed two 6-min locomotors trials on the same day: treadmill FW and BW with eyes closed and opened. Treadmill walking velocity was 4km/h. Total 6 trials, 3 trials for each condition	Kinematic = Woodway treadmill, 2 electromagnetic goniometers, an inclinometer. Force plate = instrumented plantar insoles, computed sway path.
13.	Masumoto et al. [2007]	N= 10m Age= 23.5(1.4)y Height = 176.6(4.4)cm Weight= 72.6(11.1)kg Fat= 20.6(5.2)%	Participants completed 1 min exercise bouts for each 4 modes FW and BW in water, with and without water current. Performed waking on 3-speed settings 1.8, 2.4 and 3.0 km/h with 1min rest between each speed.	Others = Flowmill 1200D EMG = Nihon kohden. Muscles = GMED, VM, BF lh, TA, GAS L, RA and PS level L4.
14.	Nadeau et al. [2003]	N= 11 [5m, 6f] Age= 27.6(4.2)y Height = 171.6(12.2)cm Weight = 64.9(18.5)kg	Participants were simply asked to walk FW and BW either on a foam rubber or hard ground with their eyes open or closed.	Kinematic = ELITE system, 2 video cameras.
15.	Chen et al. [2000]	N= 16m Age= 21(2.95)	Record the data of the 5different walking patterns, 1.FW 2.BW 3.FWT 4. BWT 5. B.W.T.I on inclined 10% treadmill.	Kinematic = infrotronic ultra flex gait analysis system. Force plate = computer dynography EMG = sample frequency 1000HZ Muscles = RF,HAM,TAandGAS Analysis = only in right leg.
16.	Grasso et al. [1998]	N= 7 [3m, 4f] Age= 31year Mean age	Participants were instructed to walk barefoot with arm folded on a chest at freely chosen speed. FW and BW were performed in 3 to 5 trials.	Kinematic = ELITE system with 4, 100HZ tv camera Force plate = piezoelectric force plate EMG = bandpass filter Muscles = GM, BFlh, RF, GAS L, TA, and VL.
17.	Schot et al. [1998]	N= 11 [5m, 6f] Mean Height = 1.74(0.09) Mean Weight = 718(99)	Participants walked 15-20 min continuously along a marked 14m lane, turning around at the boundaries, so as to maintain FW and BW.	Kinematic = photoelectric transceivers interfaced to an A/D converter 100HZ.

18.	Van Deursen et al. [1998]	N= 4 [2m, 2f] Age= 31(3)y Height = 170.3(8.8)cm Weight = 62.2(9.4)kg	Participants walked on the treadmill during FW and BW.	Kinematic = Quinton treadmill, a lighted metronome that kept a rhythm of 114 counts per minute, 4 electro goniometer. Force plate = foot switch EMG= 6channel system 600Hz sampling frequency Others = Lab view and MATLAB software Muscles = BF, SOL, RF, VL, TA and GAS L Analysis = only in the right leg.
19.	Thorstensson et al. [1986]	N= 5 [4m, 1f] Age= 25-30 years' male, 20 years'female	Participants performed FW and BW on a motor-driven treadmill at constant speed ranging from 1.0 to 2.0 ms-1.	Kinematic = Selspot optoelectronic system, infrared light emitting diodes 156HZ frequency Force plate = pressure sensitive transducer connected to a flexible tube, glued on to an outer perimeter of each shoe. EMG = recorded with surface electrodes Muscles = GM, HAM, RF, VL, GAS L and TA Analysis = only left leg.
20.	Kramer et al. [1981]	N= 1m Age= 28y	1 The participant has examined 9 trials of normal FW and BW patterns.	Kinematic = 2 photosonic model movie cameras 60 frames/s. Others = 4 channel oscilloscope EMG = Tektronix 20 to 2000HZ Muscles = RF, VL, VM, HAM, HAM M, HAM L, GM, GAS M, PL, TA, GMED and Hip adductors.

N= number, y= years, m = male, f = female, EMG = electromyography, TA =tibialis anterior, SOL = soleus, GAS L = gastrocnemius lateral, VL = vastuslateralis, VM = vastusmedialis, BF = biceps femoris, RF = rectus femoris, SM = semimembranosus, HAM = hamstring, iliopsoas, GMED = gluteus medius, GM = gluteus maximus, TP = tibialis posterior, RA = rectus abdominis, PS = paraspinalis, GAS = gastrocnemius, DOF = degree of freedom.

3.3 Risk of bias within and across studies

3.3.1 Quality assessment using the Joanna Briggs Institute Meta-Analysis of Statistics Assessment and Review Instrument (JBI-MAStARI).

The detailed critical appraisals of each of the studies are shown in Table-2. All twenty studies were evaluated by the descriptive design JBI-MAStARI tool. Overall, the majority of the included studies scored 6. After discussion between reviewers, 100% agreements among the items were attained. All articles adequately reported the items as follows:

Table - 2 Quality assessment using the JBI-MAStARI

No	Author-year	Total	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9
1.	Błażkiewiczet al. [2013]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
2.	Hidefumi et al [2013]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
3.	Lee et al. [2013]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
4.	Naoki Soda et al. [2013]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
5.	Bolton et al. [2012]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
6.	Jansen et al. [2012]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
7.	Zonthichaiet al. [2012]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
8.	Carneiro et al. [2010]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
9.	Jansen et al. [2010]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
10.	Katsavelis et al. [2010]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
11.	Maeda et al. [2010]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
12.	Nunzio et al. [2009]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
13.	Masumoto et al. [2007]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
14.	Nadeau et al. [2003]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
15.	Chen et al. [2000]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
16.	Grasso et al. [1998]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
17.	Schot et al. [1998]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
18.	Van Deursenet al. [1998]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y

19.	Thorstensson et al. [1986]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y
20.	Kramer et al. [1981]	6/8	N	Y	Y	Y	NA	N	Y	Y	Y

Y= yes, N = no, NA = not applicable

For item 1 (‘was study based on a random or pseudo-random sample?') a ‘no' rating was given to all the studies. In the studies included, all the participants were healthy volunteers who were not randomised into groups. For item 2 (‘were the criteria for inclusion in the sample clearly defined?') a ‘yes' rating was given as all the participants were in good health and above 18 years of age. For item 3 (‘were confounding factors identified and strategies to deal with them stated?') all studies identified confounding factors and dealt with them. For Item 4 (‘were outcome assessed using objective criteria?') all outcomes were assessed using objective criteria. For item 5 (‘if comparison are being made, were there sufficient descriptions of the groups?') a ‘not applicable' rating was given as the selected included studies have only one group, so there was no comparison between groups. For item 6 (‘was follow up carried out over a sufficient time period?') a ‘no' rating was given to all studies as data were collected in a cross-sectional fashion in all cases. For item 7 (‘were the outcome of people who withdrew described & included in the analysis?') a ‘yes' rating was given if the author stated that all participants who withdrew were included in the analysis or it became clear in the result section that the whole population was included in the analysis. In all studies, outcomes were measured in a reliable way (item 8: ‘were outcomes measured in a reliable way?') and appropriate statistics were used (item 9: ‘was appropriate statistical analysis used?').

3.3.2 The evaluation of the biomechanical methods by quality assessment tool

The questions and the outcome results for the quality of the kinematic, kinetic and EMG gait analysis methodologies are displayed in Table-3. Overall scores ranged between 3 and 6. Spatiotemporal data, movement task and equipment details were reported consistently within the specific parameters of walking speed, the number of walking trials and equipment configuration, respectively. Measurement of joint position and motion between segments were accurately described and in most studies, the details were stated in the procedures and graph captions. In some studies, joint position and motion between segments were extracted from the graph of one full gait cycle. The reflective markers and electrode placement that were used in 15 studies were clearly stated in the methods. In the three studies, an electro-goniometer was used to measure joint angles (26,82,158). The remaining two studies did not analyse the kinematics and EMG (95,159).

Table - 3 The evaluation of the biomechanical methods by quality assessment tool

No	Author year	Total	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7
1.	Błażkiewiczet al. [2013]	6/7	N	Y	Y	Y	Y	Y	Y
2.	Hidefumi et al [2013]	4/4	NA	Y	Y	Y	Y	NA	NA
3.	Lee et al. [2013]	6/7	N	Y	Y	Y	Y	Y	Y
4.	Naoki Soda et al. [2013]	6/7	N	Y	Y	Y	Y	Y	Y
5.	Bolton et al. [2012]	5/5	NA	Y	Y	Y	Y	Y	NA
6.	Jansen et al. [2012]	6/7	N	Y	Y	Y	Y	Y	Y
7.	Zonthichaiet al. [2012]	6/7	N	Y	Y	Y	Y	Y	Y
8.	Carneiro et al. [2010]	6/7	N	Y	Y	Y	Y	Y	Y
9.	Jansen et al. [2010]	4/4	NA	Y	Y	Y	Y	NA	NA
10.	Katsavelis et al. [2010]	6/7	N	Y	Y	Y	Y	Y	Y
11.	Maeda et al. [2010]	5/5	NA	Y	Y	Y	Y	Y	NA
12.	Nunzio et al. [2009]	5/5	NA	Y	Y	NA	Y	Y	Y
13.	Masumoto et al. [2007]	4/4	NA	Y	Y	Y	Y	NA	NA
14.	Nadeau et al. [2003]	6/7	N	Y	Y	Y	Y	Y	Y
15.	Chen et al. [2000]	4/4	NA	Y	Y	Y	Y	NA	NA
16.	Grasso et al. [1998]	6/7	N	Y	Y	Y	Y	Y	Y
17.	Schot et al. [1998]	3/3	NA	Y	Y	NA	Y	NA	NA
18.	Van Deursen et al. [1998]	5/5	NA	Y	Y	NA	Y	Y	Y
19.	Thorstensson et al. [1986]	5/6	N	Y	Y	NA	Y	Y	Y
20.	Kramer et al. [1981]	5/6	N	Y	Y	NA	Y	Y	Y

Y= yes, N = no, NA = not applicable

Item 1 Skill of the assessor stated

Item 2 Description of spatio temporal /EMG data

Item 3 Explanation of movement task

Item 4 Define marker/electrode placement

Item 5 Equipment details

Item 6 Measurement of joint position (start and end place)

Item 7 Reference planes or motion between segments

3.4 Results of individual studies

Most research on movement analysis of BW and FW has been based on quantitative and descriptive observation.

3.4.1 Kinematics

The kinematic behaviour of the lower limb joint angles and trunk angle were analysed for walking in nine studies. All these studies measured only sagittal plane joint angles. The five studies were compared with the quantitative SMD method, two studies were compared through correlation coefficient method and the other two studies explained kinematics through qualitatively discussed. The calculated SMD value for the kinematic parameters is shown in Figure-2. Only one study measured elevation angle of thigh, shank, and foot and reported that there was no significant difference between BW and FW on the ground (25). The joint angles of the hip (SMD 0.00,-0.45 r 0.99) (25,40,159) and knee (SMD 0.55, r 0.95) (25,40) show higher correlation and no significant difference, whereas the ankle joint angle was significantly different from FW to BW with lower correlation (r 0.65) (40).The SMD value shows higher ankle dorsiflexion (SMD1.37) (153). One study (159) measured lower trunk inclination (SMD -2.00) during BW than FW on the ground. One study measured both FW and BW joint angles at the stage of initial contact and final stance in water and ground environment (160). The calculated SMD value shows that during initial contact, the knee (SMD 5.37) and ankle angle (SMD 2.64) is more and hip angle (SMD -2.65) is less in FW. It is vice versa during final stance of BW had knee (SMD -7.48), ankle angle (SMD -0.39) is less and hip angle (2.87) is more than FW. Two studies reported (82,158) hip extension (BW: 10º, FW:16º), hip flexion (BW: 25º, FW:26º), knee extension (BW: 2º, FW:3º), knee flexion (BW: 67º, FW:71º), ankle dorsiflexion (BW: 22º, FW:12º) and ankle plantar flexion (BW: 6º, FW:16º). Thus the studies reported that BW ankle joint angle was in more dorsiflexion in all environments when compared to hip and knee flexion angle.

The following one study measured total RoM: The SMD value calculated from Lee et al also show significant reduction of hip joint RoM (-2.04), knee joint RoM (-2.02) and ankle joint RoM (-2.99) during BW (23). Thus the studies which invariably report RoM in BW are significantly fewer than those in FW (23,82,158).

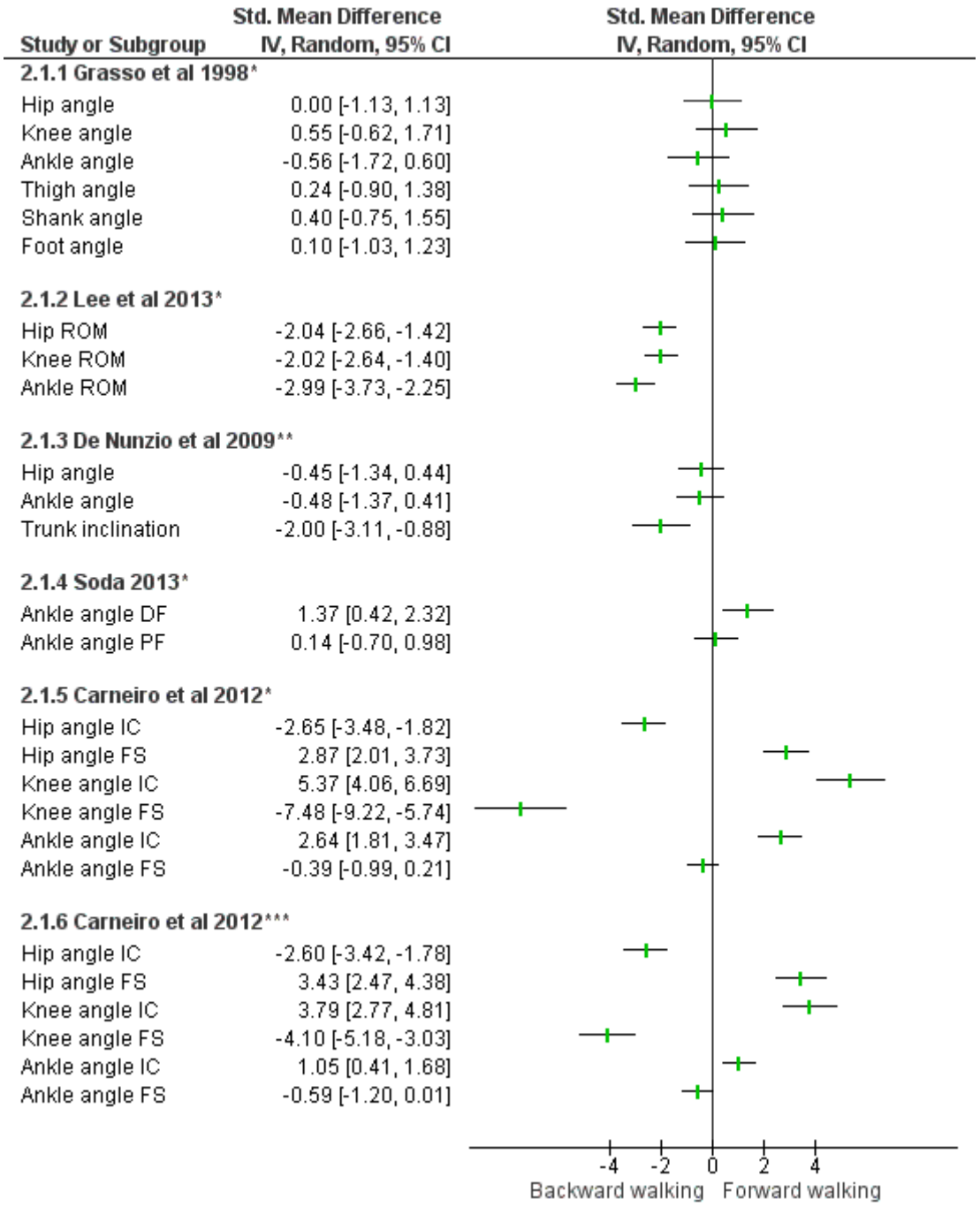


Figure-2 SMD (95% CI) of the effect of joint angle and RoM compared with BW and FW. IC = Initial contact, FS = Final stance, * = ground, ** = treadmill, *** = water.

3.4.2 Kinetics

Seven studies explored kinetics of BW and FW such as joint power, tibiofemoral joint reaction force, joint moment, joint torque, and the center of pressure (COP). Here, the five studies were compared with the SMD method (Figure 3) and the remaining two studies were compared with the correlation coefficient method.

One study (105) found that the whole gait cycle hip knee and ankle joint torque showed lower value in BW than FW. These BW value were strongly correlated and indicate a simple reversal of kinetic parameters of FW. Three studies were reported joint power of ankle, two studies established that joint power of ankle was significantly lower in BW (SMD-2.53 (153), -10.53 (23)) and inversely correlated (r = -0.86) with FW (40). The hip joint had lower power generation (SMD -2.62) in BW than FW (23) and showed a low correlation (r = -0.63) between FW and BW (40). Knee joint had similar power generation in both BW and FW (r = -0.93 (40) SMD -0.65 (23)).

Two studies measured joint moment, where the ankle (r = 0.99) (40) and knee (r = 0.73) (40) joint moment were highly correlated between BW and FW in one study. The second study found the lower joint moment in ankle flexor (SMD -0.72), ankle extensor (SMD -1.18) and knee extensor moment (SMD -0.60) during BW than FW (23). The hip joint moment (SMD 1.29) was larger in BW than FW (23) and showed a high correlation (r = 0.54) between BW and FW (40).

One study (150) measured the tibiofemoral joint reaction force at different speed. The systematic increase of speed shows that the initial domination of BW reduced significantly at high speed. Another one study (159) measured COP displacement of 1st stance (SMD 4.93) and 2nd stance (SMD -7.64) which showed almost symmetrically reversed characteristics of between BW and FW.

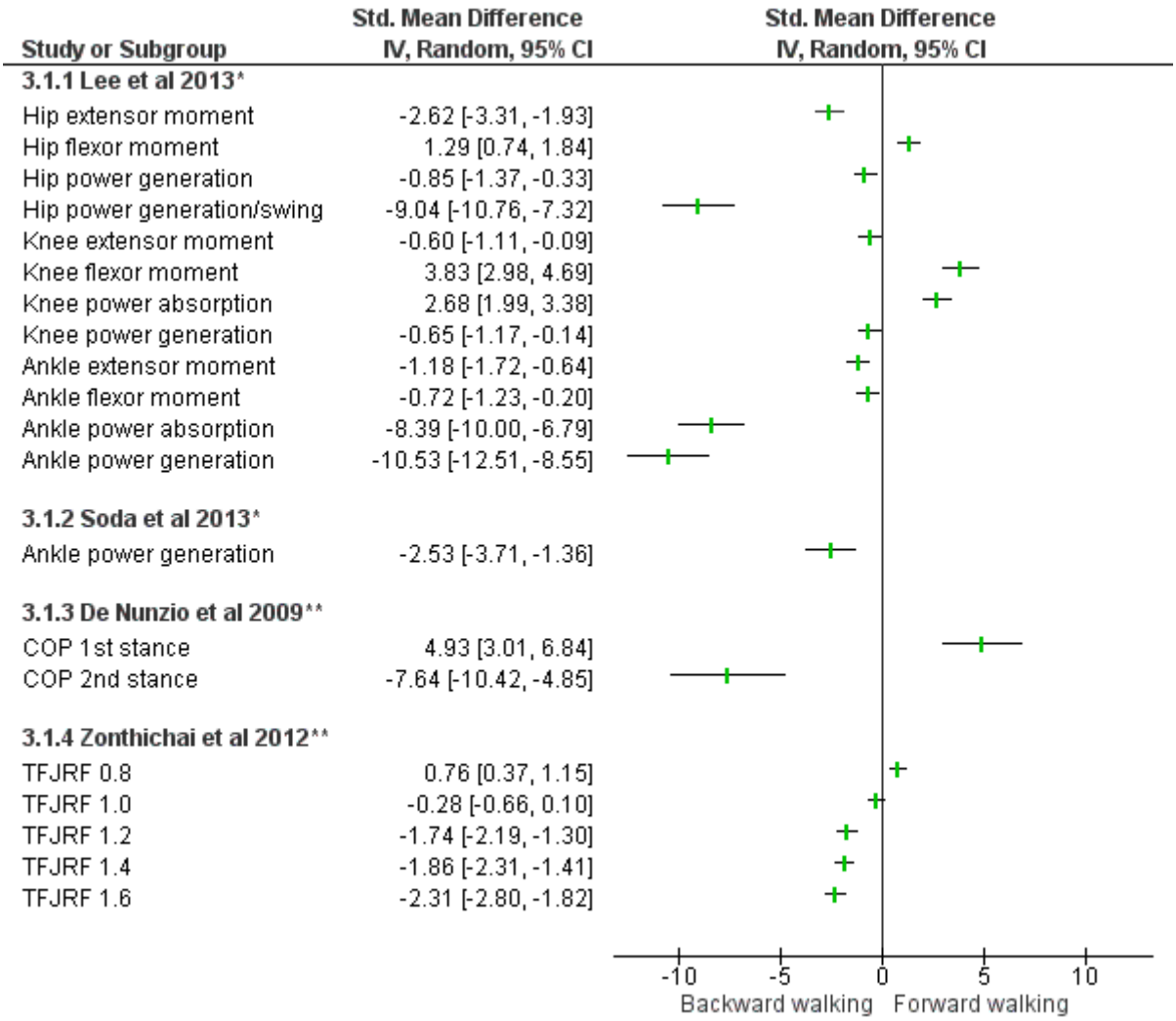


Figure-3 SMD (95% CI) of the effect of the joint moment, joint power, COP, and TFJRF compared with BW and FW.

COP = center of pressure, TFJRF = tibio femoral joint reaction force,* = ground, ** = treadmill, *** = water.

3.4.3 Muscle activity

Muscle activity was investigated in twelve studies. Three studies were calculated muscle activity through the SMD method; two studies were calculated muscle activity through the RMS with correlation coefficient method and remaining studies are discussed in descriptive form due to unavailability of mean and standard deviation. The muscle activities of the SMD are shown in Supplementary figure 2 and 3. The calculated SMD value show more muscle activity in BW than FW exist while muscle activity increasing as the walking speed increases on ground and in water. Except for gluteus maximus (GM) (SMD-0.63), gastrocnemius (GAS) (SMD-1.40) and biceps femoris (BF) (SMD-0.51) all other muscles show lower contraction in BW than FW

(25,110). The walking speed gradually increased with the BF muscle activity (SMD -0.43, 1.25, 1.93, 2.13) in BW (110).

Two studies (40,105) reported that the muscle activity in the tibialis anterior (TA) (RMS 0.16), GM (RMS 0.04), BF (RMS 0.19,r 0.8) and semitendinosis (ST) (r 0.91) muscles were not significantly different with higher correlation during BW and FW. However, GAS (r 0.39) and soleus (SOL) (r 0.27) muscles show lower correlation during BW than FW on ground and treadmill (40).

One study (149) found that during BW in water for various speed of walking, the muscle activity of the paraspinal muscles (PS) (SMD 0.55 to 0.92), vastusmedialis (VM) (SMD 0.66 to 1.67) and TA (SMD 0.61 to 1.20) showed significantly greater activity during BW than during FW (149). In effect, the outcomes show increased muscle activities in TA, SOL, PS, VM, rectus femoris (RF) and Gmed whereas, reduced activities in GM, BF, GAS, and LGAS during BW.

3.4.4 Ground reaction force

Five studies described the ground reaction force (GRF) of FW and BW. Four of these studies were compared to the SMD method and remaining one study discussed in descriptive form due to unavailability of mean and standard deviation. The GRF of SMD method analysis is shown in Supplementary figure 4. During BW, the 2nd stance phase of GRF in vertical reaction force and longitudinal shear force of the SMD value (-1.47 to -0.66) are reduced than 1st stance phase of GRF in BW and FW (25,150,159,160), while BW in water shows no significant difference from FW in water.

3.4.5 Gait parameters

Nine studies described the gait parameters of FW and BW. The four studies were compared with the SMD method and remaining five studies discussed in descriptive form due to unavailability of mean and standard deviation. The gait parameters of SMD method analysis are shown in Supplementary figure 5. During BW step time (SMD 0.54) and stride time (SMD 0.99) were significantly increased than during FW (23,153).The other parameters of walking speed (SMD -1.97), cadence (SMD -1.21 to -3.64) and stride length (SMD -0.99) were significantly reduced in BW than FW (23,25,160). In effect during BW the stance time is increasing, to reduce the walking speed and length.

4. Discussion

This is the first systematic review that reports on the biomechanical comparison of BW and FW. A total of 20 articles were included in the present review based on the systematic search method applied in this study. The findings from these 20 articles are discussed in this section.

4.1 Risk of bias within and across studies

The observational studies included in this systematic review were critically appraised. The quality assessment by JBI-MAStARI of all 20 included studies had the low risk of bias and used appropriate methods to establish the outcomes and the data was reliable.

The evaluation of the biomechanical methods by quality assessment tool shows that the quality of the studies ranged between moderate and high. This indicated that the experimental methodology was generally repeatable. However, these 20 studies did not report on information pertaining to the level of skill of the assessor, which is essential as specialised knowledge and training is required to carry out the 3D gait analysis.

4.2 Study characteristics

The participants' age and BMI were necessary to evaluate the biomechanical characteristics of walking (161). In this review, all studies included study participants' age ranges 18 to 40, while increasing the age declines in walking performance and mechanics of gait (162,163). The chosen age ranges were most suitable to analyse the biomechanical parameter of walking (164).

4.3 Outcome measure

The outcome measures of kinematics, kinetics, muscles activity, GRF and gait parameters will be discussed to elaborate the difference between FW and BW. The data obtained from mean ± SD were synthesized by the SMD method (Figure 2,3, and Supplementary figure 2 to 5). The data collected from the qualitative comparison, correlation coefficients and RMS were discussed without further data synthesis.

4.3.1 Kinematics

In this review, the studies on kinematic parameters were based on 2D or 3D analysis of FW and BW. During FW the leg movement starts at heel strike and ends at toe off but during BW the leg movement starts at toe strike and ends at heel off (25,40,82). During BW all limb segments rotated counter clockwise at stance phase and clockwise rotation occurred at swing phase; vice versa during FW (25). This different BW pattern transferred less shock to the knee joint (42). This tended to occur with smaller amplitude of joint angles and significantly reduced RoM in BW than FW as shown by SMD value in Figure 2.

While walking backward the hip joint angle showed less extension at the stage of loading response and greater flexion during heel off. At the same time, the hip was less flexed in initial contact and there was less extension in the pre-swing stage of BW (23,25,158). The knee joint flexion angle was almost monotonic during BW stance phase and highly correlated with FW but with a lower range of motion (23,25,26,40,105,158). One conspicuous difference was the limited knee flexion during the swing phase on treadmill BW (82). So the compressive forces are reduced on the knee. The reduced compressive force helps to reduced knee osteoarthritis pain (37) and these hip and knee joint movement pattern also contributed to improved neuromuscular control for patients with hemiparesis (38). The ankle joint was more dorsiflexion after the toe strike and plantar flexion during loading response of BW than FW (23,25,105,153,158).

The biomechanical characters were found to change with environment and external factors. The significant differences in the kinematic parameters of joint angles were analysed and reported for BW and FW. During BW the joint angle in water was greater than ground and treadmill (160). Varying visual cues like closing the eyes resulted in greater joint angles during BW than FW (98,165). These environmental changes help to improve neuromuscular control, proprioception and protective reflexes because of the elimination of visual cues (38).

4.3.2 Kinetics

During walking the mechanical force, moment, power, torque, and CoP excreted in lower limbs are considered as the kinetic parameters. The calculated SMD are shown in Figure 3. The CoP shows higher SMD value for 1st stance and lower in the 2nd stance of BW than the FW. It is stated that during BW the COP moved from toe to heel and during FW it moved from heel to toe (159). This direction of weight transfer in BW creates continuous descend of the vertical COM for a long time and reach a lower vertical level for BW propulsion.

The displacement asserted by walking creates the forces in lower limb joints. The average TFJRF were found to be lower in BW than FW. The large SMD value obtained from the comparison of BW with FW at elevated speed show the small increases of TFJRF in BW (150). The average lower TFJRF during BW helps to reduce the chronic knee injuries. Therefore BW could be considered as a rehabilitation programme for tibiofemoral joint problems (150).

The knee and ankle joint torque was lower in BW and highly correlated with FW (105). The calculate SMD value for the maximum power generation in hip, knee and ankle joints were significantly smaller in BW than FW (23,153). The analysis of the BW data shows the ankle joint had both power generation and absorption is much higher than hip and knee. These indicate that the ankle might be the significant point for propulsion and shock absorption (23).

In contrary, Soda et al concluded that propulsive force was compensated through the hip power and center of gravity. In both trials, smaller knee joint power was understood from the simpler pattern of knee joint displacement in BW (23).

Except ankle joint flexor moment, all other flexor and extensor moment for hip and knee had significantly lower SMD value for BW than FW. The joint moment in the ankle was almost identical in FW and time reversed in BW. The knee and hip joint moment were time reversed and simpler in BW than FW (23). These differences in joint moment of the proximal joints induced the reversal of joint acceleration and changed individual muscle function from energy generator to absorber between FW and BW (40).

4.3.3 Muscle activity

The muscle activity parameters were calculated by SMD method for analysed eleven muscles in different walking surfaces as shown in Supplementary Figure 2 and 3. During BW the GM, GAS and BF muscles showed lower activity or did not favour SMD value when compared to FW (25,110). When BW speed is increased, the BF muscle activity also gradually increases. The lower GM muscle activity leads to reduced hip extension and flexion moment during the BW stance phase and thus prevents abnormal loading at the knee joint (36). The GAS muscle help to pull the leg backward from midstance to heel off phase (22). It also absorbs impact energy during eccentric contraction and leads to control of ankle dorsiflexion movement in BW (22,48,158). Except for the above mentioned muscles, all other studied muscles show more activity during BW than FW on all the surfaces (25,110,149).

Two studies identified the effect of muscle contribution for acceleration of COM. During double limb support phase of BW, the rectus femoris (RF) and vastuslateralis (VL) accelerate the COM whereas the GAS and SOL decelerate the COM during BW. In the single limb support phase, the SOL muscle was the main accelerator for the COM and TA was the main decelerator of the COM in BW. However during vertical acceleration the TA muscle decelerated the COM in double limb support phase of BW and during single limb support Gmax, Gmed, TA muscles showed acceleration and GAS, SOL decelerates the COM during BW (40,166).

All these muscle activities and COM during BW indicate that due to different muscle synergies, a different amplitude of muscle activity and muscle force, BW is not a simple reversal of FW (25,105). The increased muscle activity show that participants' energy expenditure, mechanical power, heart rate and oxygen consumption was higher in BW than FW (149). Which make BW an ideal rehabilitation exercise for cardiopulmonary disorders, stroke, obesity and osteoarthritis (36,38,42,143).

4.3.4 Ground reaction force

In BW, the lateral GRF is directed forward, when the toes make contact with the ground and decelerate the body during early stance. The GRF is close to zero during midstance (25). The vertical GRF produces two peaks in the support phase. The first peak is caused by body weight loading and is always higher in BW than FW and the second peak is smaller in BW than in FW as it is caused by heel off with impulse generation of knee extensor muscles in BW. This relates to the increase in the first peak of vertical GRF in BW due to sudden discharge of the ipsilateral limb movement on initial contact. Also, during FW the increase in the second peak is related to strong contraction of plantar flexors at final support phase but the breaking peak was clearly higher during BW (23,150,159). Within the different environments of land and in water, GRF showed no significant differences but comparatively BW vertical GRF's second peak was larger in water than BW on land. It was concluded that BW in water was safer than land for use in balance-related diseases (160).

4.3.5 Gait parameters

In general, the gait parameters of both types of walking varied due to the asymmetry of joint movements. Differences between BW and FW calculated SMD value is found throughout the various phases of the gait cycle is shown in surfaces as shown in Supplementary Figure 5. During BW the stance time, stride time and stance phase increased because of the walking speed, cadence, stride length and gait cycle which were reduced in BW when compared to FW. During the stance phase of BW, the ankle showed more plantar flexion during the loading response than during initial contact, due to deceleration of the COM. During midstance, ankle plantar flexion was used to move the trunk backward when the plantar flexors (GAS, SOL) were active (25,153). From initial contact to midstance, the knee flexed and extended, again flexed in terminal stance and extended in pre-swing to prevent descent of the COM. In this phase, the knee extensors (VL, VM, and RF) were active (23,82). During initial contact to loading response, the hip moved from extension into flexion then again from flexion into extension at terminal stance. In order to maintain the trunk in a vertical position, during the terminal stance phase, the HAM muscle was active (23). During the BW swing phase, the ankle moved from dorsiflexion into plantar flexion at the terminal swing, knee flexion was present at initial swing and knee extension at the terminal swing, a hip extension was present during the entire swing phase to avoid the knee extension during BW. The stride length was shorter in BW when compared to FW because the average hip joint flexion and extension RoM varies greatly (23). Stance and stride time was increased due to decreased stride length (95). Step length

decreased due to hip and knee RoM which was decreased in BW (25). Walking speed and cadence were reduced in BW due to lack of vision and less practice (160).

4.4 Neural control of forward and backward walking

The kinematic and kinetic properties from the included studies reveal that simple reversal of FW is not sufficient to produce BW (23,25,26,39,40,82,143). Hence, the modified neural control strategies were required to produce BW from FW. Here, the BW needs additional support from central pattern generator due to anatomical constraint and visual cues than FW.

4.5 Recommendations for future research and limitations

Three recommendations aimed to improve the quality of future studies can be made from the results of this study. Firstly, future studies should specify the level of skill of the assessors who undertake 3D gait analysis. Secondly, the specifications of the lower limb and number of walking trials should be clearly stated. Thirdly, the anthropometric measurement of height, weight, and BMI should be specified to easily generalise the findings of the walking pattern for the reader. In terms of future research, more studies are needed on the comparison between ground and treadmill walking and the comparison of gait between genders. More research that aims to define kinetic factors of both walking on various surfaces and at the different speed is needed. The results from these studies would be valuable to further the understanding of the walking pattern and the results may prove useful in the rehabilitation of patients.

5. Conclusion

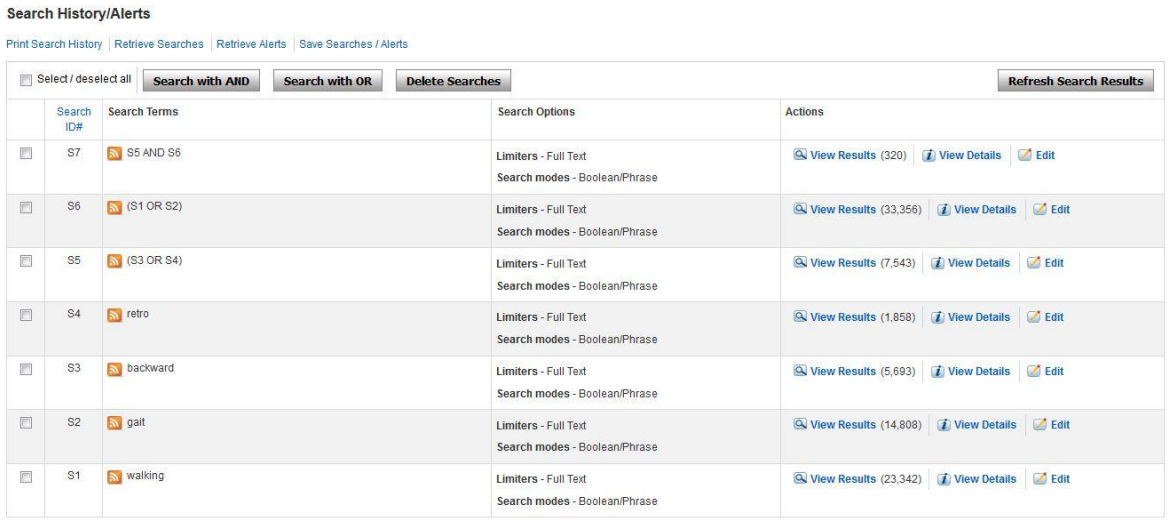
In conclusion, the present systematic review retrieved 20 observational studies from the existing literature and compared the biomechanical properties of BW with FW. It reveals BW exhibits; lower angles for knee joint flexion and ankle joint plantar flexion reduced power in ankle and hip joint, increased muscle activity, decreased GRF and gait parameters except stride frequency than FW. Hence, the modified neural control strategies were required to produce BW from FW. Each of these biomechanical outcomes from BW was reported for specific therapeutic benefits in rehabilitation. The average lower TFJRF during BW helps to reduce the chronic knee injuries while treating tibio-femoral joint problems. The increased muscle activities show the participants' energy expenditure, mechanical power, heart rate and oxygen consumption was higher in BW than FW. Hence, BW is an ideal rehabilitation exercise for cardiopulmonary disorders, stroke, obesity, and osteoarthritis. The absence of visual cues in BW also improves the neuromuscular control, proprioception and protective reflexes. The outcome shows the benefits of BW is consistently higher than FW in different environments such as, on ground,

treadmill and in water. Among the trials, BW in water yields increased lower limb joint angles, muscle activity than ground and treadmill. Moreover, the GRF indicates BW in water is safer than land for treating balance-related diseases.

6. Acknowledgements

The author gratefully acknowledges NRF fellowship (grant number 98729) and Wits PMA for the financial support. The authors thank Dr. Kamalakannan R for his valuable inputs for statistical analysis.

7. Supplementary Material



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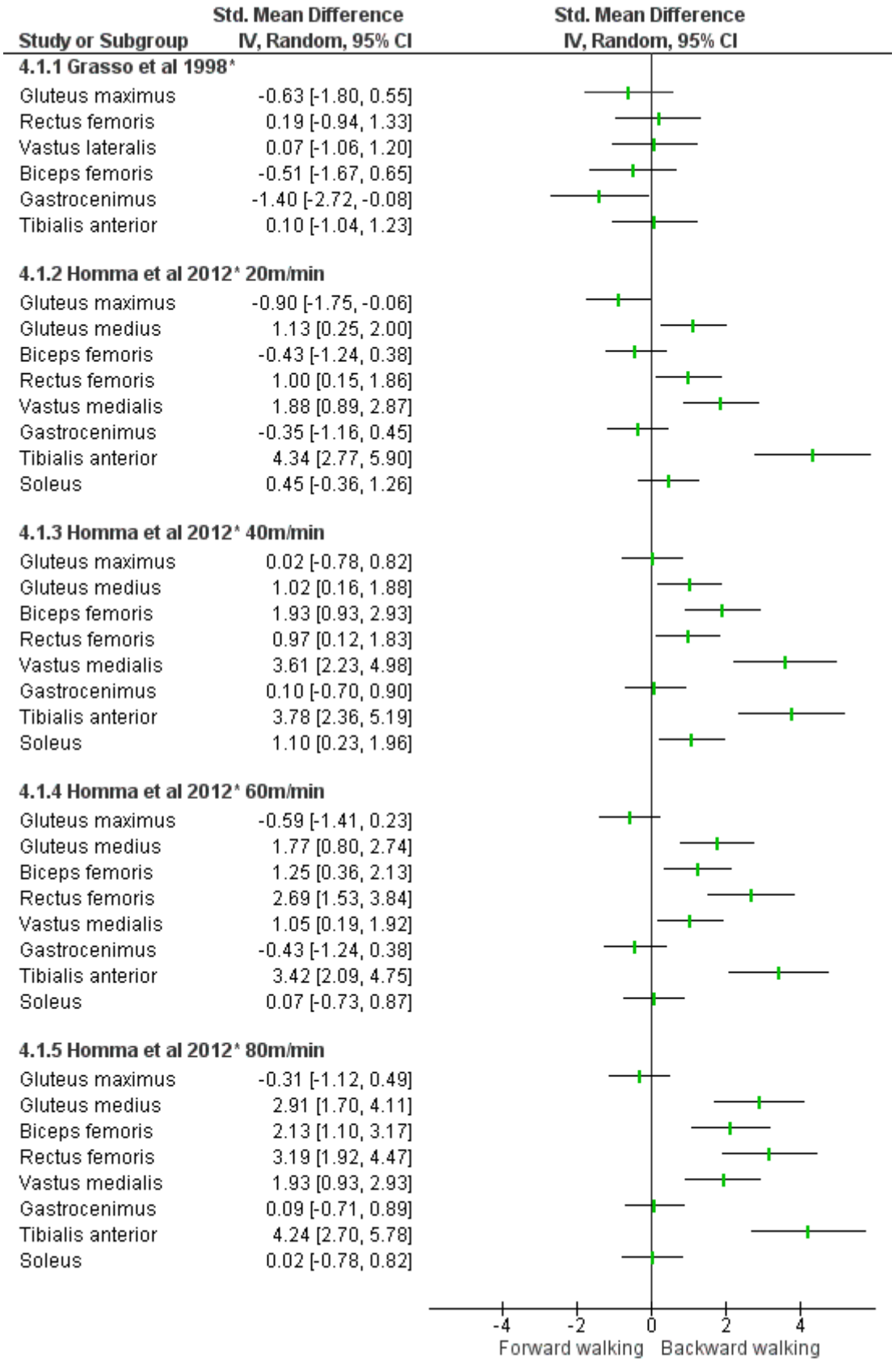
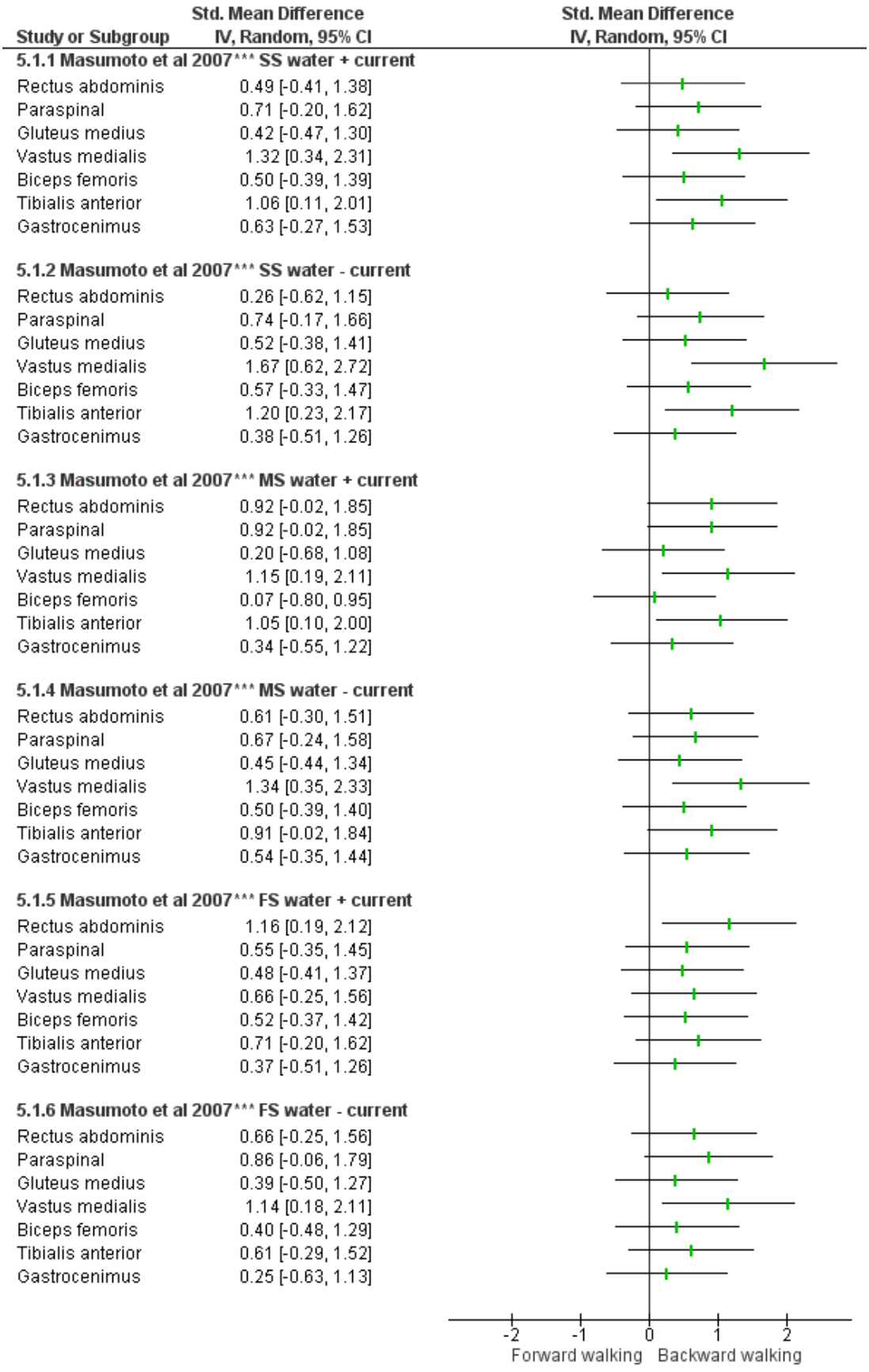
	Search ID#	Search Terms	Search Options	Actions
☐	S7	S5 AND S6	**Limiters** - Full Text **Search modes** - Boolean/Phrase	View Results (320) | View Details | Edit
☐	S6	(S1 OR S2)	**Limiters** - Full Text **Search modes** - Boolean/Phrase	View Results (33,356) | View Details | Edit
☐	S5	(S3 OR S4)	**Limiters** - Full Text **Search modes** - Boolean/Phrase	View Results (7,543) | View Details | Edit
☐	S4	retro	**Limiters** - Full Text **Search modes** - Boolean/Phrase	View Results (1,858) | View Details | Edit
☐	S3	backward	**Limiters** - Full Text **Search modes** - Boolean/Phrase	View Results (5,693) | View Details | Edit
☐	S2	gait	**Limiters** - Full Text **Search modes** - Boolean/Phrase	View Results (14,808) | View Details | Edit
☐	S1	walking	**Limiters** - Full Text **Search modes** - Boolean/Phrase	View Results (23,342) | View Details | Edit

Supplementary figure - 1 Search strategy in MEDLINE using ‘walking’, ‘gait’, ‘retro’ and ‘backward’ as keywords



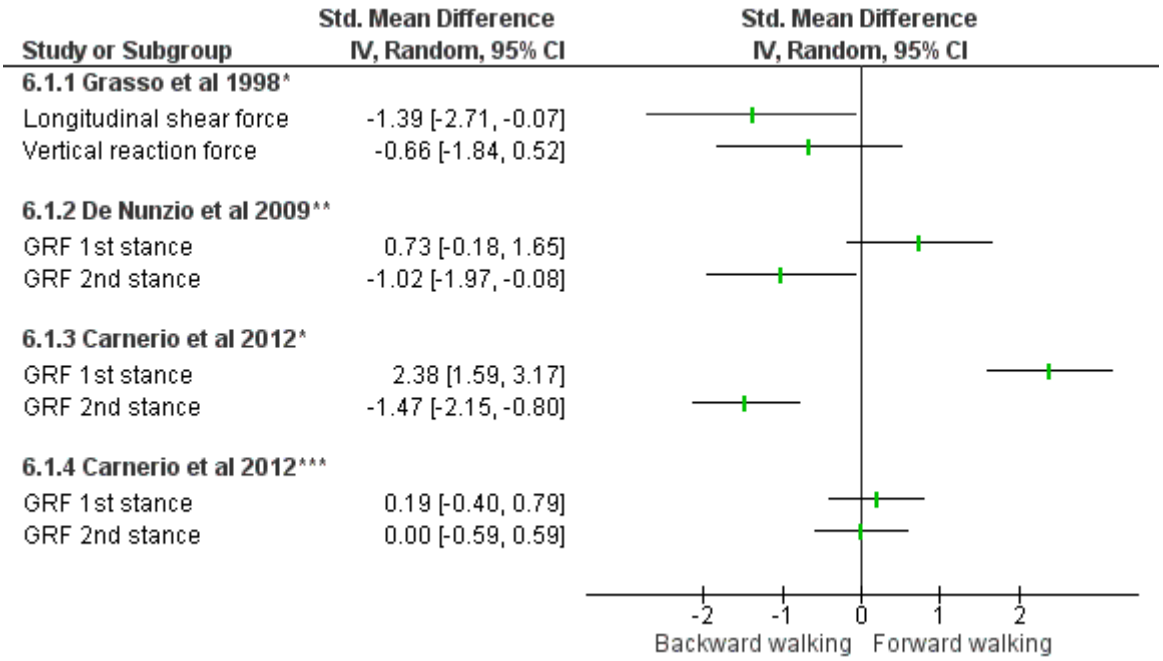
Supplementary figure - 2 SMD (95% CI) of the effect of muscle activity compared with BW and FW.

* = ground, ** = treadmill, *** = water.



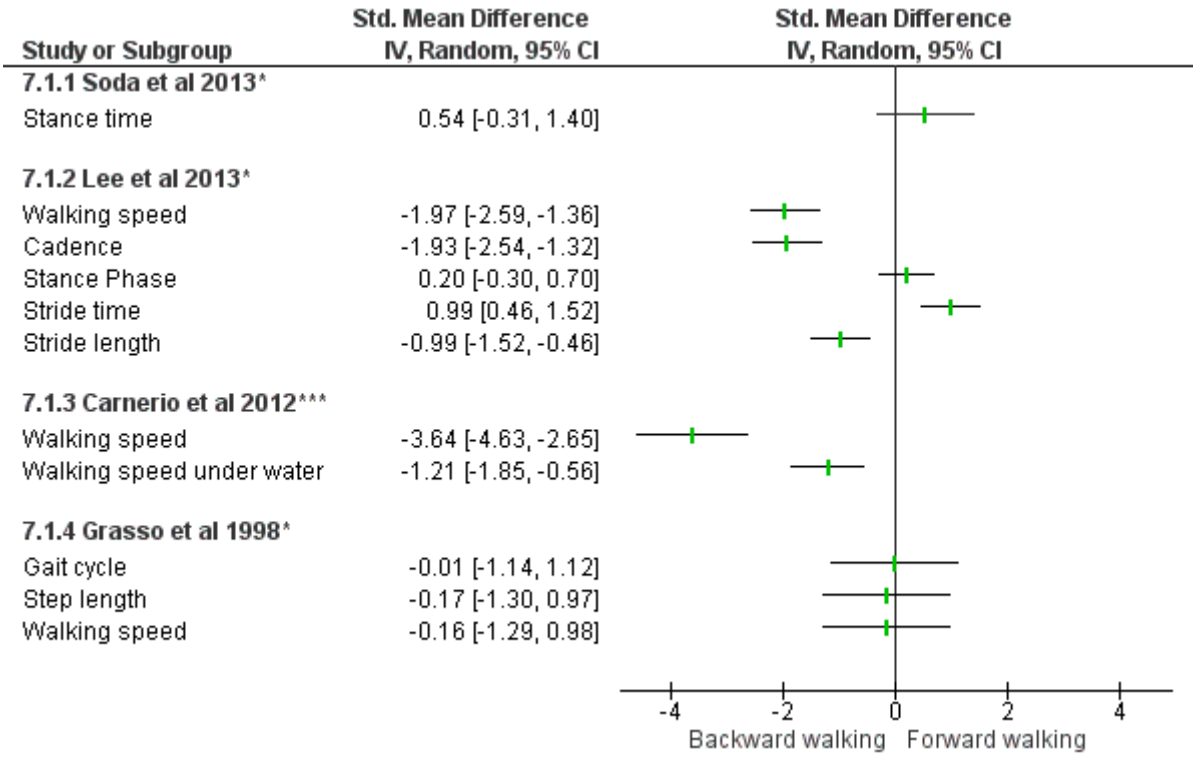
Supplementary figure - 3 SMD (95% CI) of the effect of muscle activity compared with BW and FW.

* = ground, ** = treadmill, *** = water.



Supplementary figure - 4 SMD (95% CI) of the effect of ground reaction force compared with BW and FW.

* = ground, ** = treadmill, *** = water.



Supplementary figure - 5 SMD (95% CI) of the effect of gait parameters compared with BW and FW.

* = ground, ** = treadmill, *** = water.

Supplementary table - 1 PRISMA checklist

Section/topic	#	Checklist item	Reported on page #
TITLE			
Title	1	Identify the report as a systematic review, meta-analysis, or both.	✓
ABSTRACT			
Structured summary	2	Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number.	✓
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known.	✓
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparison, outcomes, and study design (PICOS).	✓
METHODS			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number.	X
Eligibility criteria	6	Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale.	✓
Information sources	7	Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched.	✓
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated.	✓
Study selection	9	State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis).	✓
Data collection process	10	Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators.	✓
Data items	11	List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made.	X

Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis.	✓
Summary measures	13	State the principal summary measures (e.g., risk ratio, difference in mean).	✓
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I^2) for each meta-analysis.	x

Section/topic	#	Checklist item	Reported on page #
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies).	✓
Additional analyses	16	Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.	x
RESULTS			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram.	✓
Study characteristics	18	For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations.	✓
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12).	✓
Results of individual studies	20	For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot.	✓
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency.	x
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see Item 15).	✓
Additional analysis	23	Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]).	
DISCUSSION			
Summary of evidence	24	Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers).	✓
Limitations	25	Discuss limitations at study and outcomelevel (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias).	✓

Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research.	✓
FUNDING			
Funding	27	Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review.	✓

Supplementary table - 2 Questions and rationale for decisions during the methodological assessment of studies **(156,157)**.

No	Question	Rationale for decisions
1.	Were details of the assessors carrying out the all 3D gait analysis provided?	Assessors undertaking 3D gait analysis require specialised skills, such as the ability to consistently place markers and an understanding of biomechanical models
2.	Were spatiotemporal data, gait analysis and EMG (if studied) procedure methodology described?	Variables such as walking speed, time between trials, number of trials of kinematic gait analysis and statistical value of EMG signal can affect the results
3.	Were movement tasks clearly defined?	Variability in dynamic tasks can affect kinematic / EMG data, particularly in participants with movement BW
4.	Was marker/electrode placement clearly and accurately described and was the modelling technique described?	Accuracy of marker/electrode placement will improve reliability of data and reduce skin marker artefact, which relates to the artefact caused by skin movement with respect to underlying bone/muscle
5.	Was data capture equipment reported including the reporting of reliability, precision, and accuracy of equipment?	Variables such as number, type, and specifications of cameras. Marker characteristics, data processing information and EMG electrode configuration can influence testing as instrument error can present as a confounding factor
6.	Was a reference position reported?	The reference or ‘zero’ is the position from which joint movement is measured. It is required to be reported to accurately determine dynamic motion
7.	Were the segments, anatomical reference planes and motion between segments reported?	The kinematic analysis involves the description of a model that includes a series of linked rigid segments. The model used and the planes of motion investigated are essential in understanding the information presented by each study

CHAPTER 5 - The kinematics and kinetics during forward and backward walking at three levels of treadmill inclination and speed: A simulation study

The effectiveness of BW and its biomechanical characteristics were systematically reviewed in Chapter 3 and Chapter 4. The direction of walking such as forward and backward was found to be significantly different in both clinical and biomechanical outcomes. It is noted that apart from the direction of walking speed and inclination also made significant changes in kinematic and kinetic characteristics. In this present chapter, direction, speed, and inclination of walking were studied experimentally. The walking patterns were simulated and evaluated by inverse dynamics to understand the comprehensive biomechanical characteristics of FW and BW.

5.1 Introduction

Human walking is mainly driven by the neuro-musculoskeletal system (167) and is an essential activity of daily life for locomotion. Forward and backward walking offers many health benefits as a physical exercise to improve quality of life and rehabilitation outcomes (146). Forward walking (FW) has been researched more comprehensively than backward walking (BW) (147). Several experimental and simulation studies (18,101,102,106,168) reported on the biomechanical characteristics of the lower limb during FW with respect to inclination and speed. Such as, Liu et al (102) simulated the muscle contribution with respect to walking speed. They found that when walking speed was increased, both vastusmedialis and soleus muscle activity also increased. Greater stance phase knee flexion during fast walking speed caused increased vasti force, which provides support but also slowed progression, while contralateral soleus simultaneously provides increased propulsion. Lay et al (18) reported on the kinematic and kinetic analysis of FW on sloped surfaces and have shown that joint moment increased significantly during both up and downslope walking compared to level walking. The increases were predominantly due to the higher hip extensor moment during upslope walking and increasing knee extensor moment during downslope walking (169). Kuster et al (170) established that the peak moment and muscle power was much higher for downhill walking in the knee joint. This inclined surface task changes demands on the unique neuromuscular system. The research for FW is wide and covers muscle and joint mechanisms in the lower limb such as muscle activity, muscle power, joint angle, joint moment, joint force and joint power with respect to speed and various levels of inclination.

The biomechanical characteristics of the BW were described through movement analysis and the characteristics were broadly categorised into kinematics and kinetics. Between these properties, kinematics were studied by vector analysis/inverse kinematics from the position of the reflective marker (29). Whereas, model development and inverse dynamic simulation are required to calculate accurate kinetic parameters (30). For example, the simulations will establish the inaccessible muscles with accurate dynamic parameters.

The kinematic comparison of BW from vector analysis reveals that the parameters are simple time reversal of FW (23,25,39,40,82,94). Grasso et al (25) found that in FW, propulsion originated from ankle plantar flexors while hip and knee extensors provided the propulsion in the BW. Naoki Soda et al (153) reported that the propulsive force in BW is not from the ankle. Lee et al (23) have shown that the main propulsion during BW is from the ankle joint. However, muscle activity during BW shows a poor correlation to those in FW (82,110). Jansen et al (40) ascertained from neural control perspective that a simple time reversal in muscle contributions is not sufficient to produce BW from FW. Moreover, BW on an inclined treadmill reportedly requires additional muscular activity (22,48). There is no agreement in the literature about various locomotor tasks at speed, inclination, and direction of FW and BW comparison.

Limited studies exist on the motion analysis of BW compared with that of FW. Though kinematic analysis of BW has been performed, there is a lack of research on the kinetics of BW at various speeds and inclinations. FW and BW through simulation during walking at three levels of treadmill inclination and speed: (0%, -5%, +5% inclinations and 0.28m/s, 0.69m/s and 1.11m/s speeds).

5.2 Aim and objectives

To understand neural control strategies during FW and BW through calculation of biomechanical characteristics such as the kinematic parameters (joint angles) and the kinetic parameters (joint moment, joint power and muscle activity) by simulation at three levels of treadmill inclination and speed.

The objectives of this study were:

I. To determine the biomechanical characteristics of FW at three inclinations and speeds.
II. To determine the biomechanical characteristics of BW at three inclinations and speeds.
III. To compare the biomechanical characteristics of FW and BW at three inclinations and speeds.

5.3 Methods

5.3.1 Type of study

This is a simulation study aimed to establish the accurate dynamic parameters of experimentally inaccessible muscles and joints. In this study an anthropometric model was developed which represents the collected experimental data, bone geometry, joint geometry, muscle geometry, body segments, and muscle actuators to evaluate biomechanical characteristics.

5.3.2 Study setting

Data were collected at Ergonomics Technologies (ERGOTECH) Laboratory, ARMSCOR, Centurion, Pretoria, South Africa.

5.3.3 Participants

Ten participants were chosen for this study according to the sequential estimation technique to keep the accuracy within the standard deviation threshold of 0.25-0.30 (180). Participants were recruited through invitations sent to colleagues and friends. A convenience sample of ten healthy adult participants (seven males and three females) who met the inclusion criteria was included.

5.3.4 Inclusion and exclusion criteria

The inclusion criteria were male and female young adult (18-40) human with normal gait pattern participants. Because, with increasing age there is a decline in walking performance and mechanics of gait (162,163). People with recent fractures of the lower limb and spine, inability to follow instructions, impaired balance, and coordination, non-treated hypertension, previous lower limb and spine surgery, cardiovascular disease, obesity, and pregnancy were excluded.

5.3.5 Ethical considerations

Ethical clearance was obtained from the Human Ethics Research Committee of the University of the Witwatersrand (M150116) (See Appendix A). The participants were recruited according to the inclusion and exclusion criteria. Participants were informed about the purpose of this research and the testing procedure and all the possible risks that were involved with taking part in this study. Participants were also informed that they could withdraw from the study at any

time without suffering any repercussions. No monetary award was given for participating in this research project. Written informed consent was obtained from all participants (see Appendix B and C) and all information was kept confidential and anonymous. Each participant was given a study number to maintain and ensure confidentiality.

5.3.6 Instrumentation

A Bertec instrumented split-belt treadmill (Bertec, Columbus, USA) was used to collect force data and the Delsys Trigno wireless electromyography (DELSYS, Natick, Massachusetts) was used to collect muscle activity. Light reflective markers, Oqus Qualisys cameras, and Qualisys track manager software (Qualisys Medical AB, Gothenburg, Sweden) were used to capture three-dimensional data. Biomechanical models were built in Visual3D version-5 software (C-motion Inc., Kingston, Canada) and OpenSim version-3.3 software (http://opensim.stanford.edu) was used to simulate the experimental data.

5.3.7 Outcome measures

The following were measured in this study: Joint angle (kinematics), joint moment, joint power and muscle activity (kinetics) and step length, gait cycle time, step time and double limb support (temporal and spatial gait parameters). All the kinematic and kinetic measurements were taken in sagittal plane movement. More information on each of these outcomes follows:

I. Joint angle measured between the longitudinal axis of two adjacent segments. A fully extended position is defined as 0 degrees.
II. Joint moment measured from the net effect of the positive agonist or negative antagonist muscle forces and associated moment arm lengths.
III. Joint power is the scalar product of the net joint force and the joint velocity.
IV. Muscle activity was calculated by inverse dynamics procedure in OpenSim.

5.3.8 Experimental setup

Experimental setup is shown in Figure 5.1

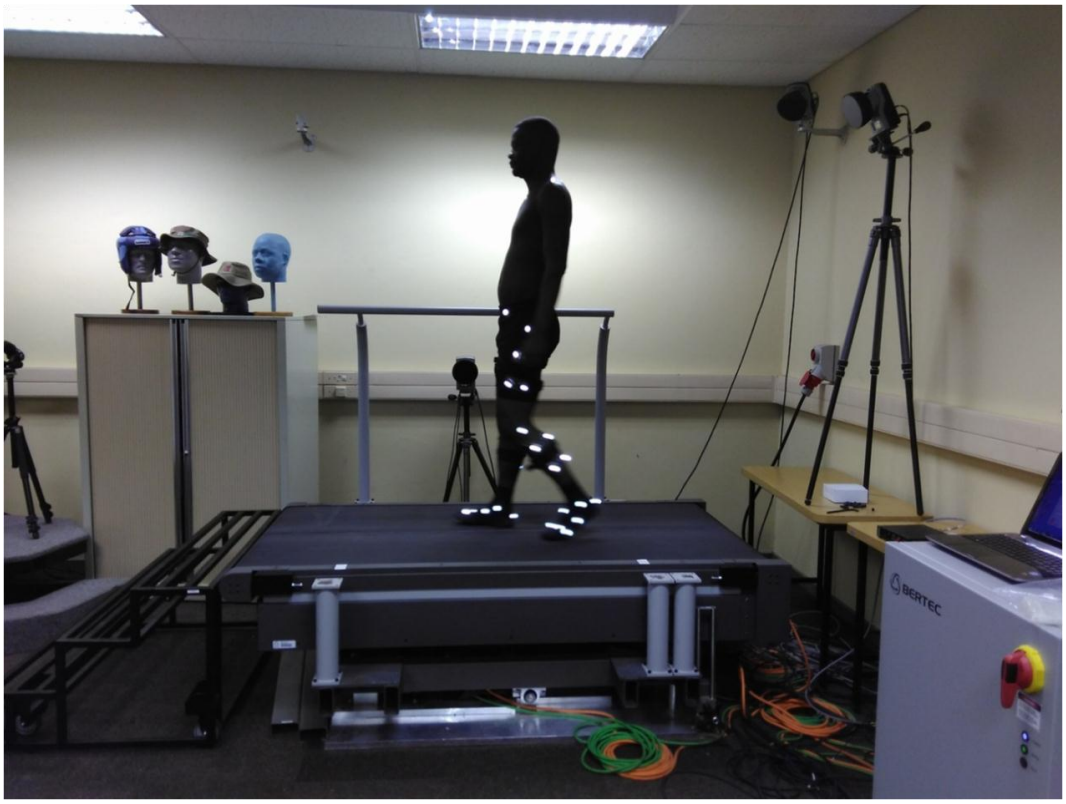


Figure 5.1 The experimental setup with synchronised Qualisys cameras, EMG, and split-belt instrumented treadmill.

Three-dimensional kinematic data were collected at 200 Hz with seven Oqus Qualisys cameras tracking the movement of reflective markers. Force plates integrated into the Bertec split-belt treadmill measured ground reaction force and torques at 1000 Hz. EMG activity was recorded bilaterally from tibialis anterior, lateral gastrocnemius, biceps femoris and rectus femoris muscles with the use of a Delsys Trigno wireless EMG system (Figure 5.1). Gluteus maximus, gluteus medius, and iliacus muscle activity were simulated from the anthropometric generic model through OpenSim software. The EMG and force plate were synchronised with Qualisys cameras.

5.3.9 Pilot Study

5.3.9.1 Objective

A pilot study was conducted to familiarise the investigator with the instruments, standardise the experimental procedure, and determine the feasibility of the laboratory procedures and to identify any potential challenges during the data collection and analysis phase.

5.3.9.2 Procedure

The pilot study was conducted at the ERGOTECH laboratory. One participant who met the inclusion criteria was recruited through friends for the pilot study. The participant was required to sign the informed consent form followed by the following items: recording of age, measuring and recording of height and weight. The entire gait analysis system was calibrated before the participant started walking. The participant practiced walking forward and backward on the ground for three minutes and then walking on the treadmill at self-selected speed to warm up for five minutes. This was followed by skin preparation for attachment of the EMG electrodes. The EMG electrodes, full body Plug-in-Gait markers and tracking markers were attached to the participant. Then the participants were asked to do two static trials, followed by treadmill walking at four speeds (0.28 m/s, 0.69 m/s, 1.11 m/s and1.38 m/s) for each of the five inclination levels (-10%, -5%, 0%, +5 %, +10%). It was observed that both participants were found difficulties while walking backward without the use of hold handrails for more than 5% inclination at higher speed. It is consistent with available BW studies which were used more than 5% inclination only in participant comfortable speed (22,24,49). Hence, the main study includes three specific inclinations and speeds for forward and backward walking. The procedure was described in section 5.3.10.1 (Experimental procedure).

5.3.9.3 Data processing, anthropometric model development and simulation

The collected data were processed in Qualisys track manager software. Here, the reflective markers in static and motion files were identified with specific names and saved in c3d format. The anthropometric models were developed in two steps by using Visual3D and OpenSim software packages. As a first step, to build six degrees of freedom (DOF) model, the c3d files were imported into the Visual3D software. While building the model, it was noticed that the thorax and foot segment were not perfectly matched with the proximal segment. This built model was exported to OpenSim and followed the simulation protocols. The following were observed during the pilot study: 1) scaling of the generic model to experimental model was

matched successfully, 2) while loading the motion file it was noticed that the model's foot and thorax were inverted and hanging. The different types of segment co-ordinations were changed to correct the pose. However, the foot was plantar flexed even though the model was walking, 3) the execution of the reduced residual algorithm (RRA) showed tool execution failure within few seconds.

To improve the model and rectify the execution failure one more pilot study was done with the same participant. In the following changes: 1) Visual3D marker set was used instead of plug-in –gait marker set. This marker set consists of 52 reflective markers which include tracking markers for continuity of the segments and iliac crest marker to fix the thorax, 2) Motion in Visual3D setup files was defined in a +Y direction. Hence, the lab coordination in Qualisys track manager software was altered to set the participant walking along +Y direction instead of default +X direction, 3) reduced the number of frames from 3000 to 1500 for 15seconds to reduce the computation capabilities, 4) the participant walked forward and backward at only 0.69m/s speed in level walking, 5) collected the participants' anthropometric data accurately to build the Visual3D model, 6) before building the model, marker data was interpolated for missing points and analog data was filtered by low-pass filter to remove high-frequency noise.

The above-modified procedure provided a perfect anthropometric model without any discontinuity between the segments. However, execution of RRA showed tool execution failure. To resolve this error, the force plate coordinates were rotated 180°. At this stage, the experimental setup was considered ready for the main study data collection process.

5.3.10 Main Study

Participants completed the informed consent form and data collection sheet (see Appendix D) after which anthropometric measurements were recorded (see Appendix E). These were completed during the warm-up session eight minutes before placement of EMG electrodes and reflective markers. The data collection was conducted by the researcher.

5.3.10.1 Experimental procedure

The experimental procedure flow diagram is shown in Figure 5.2.

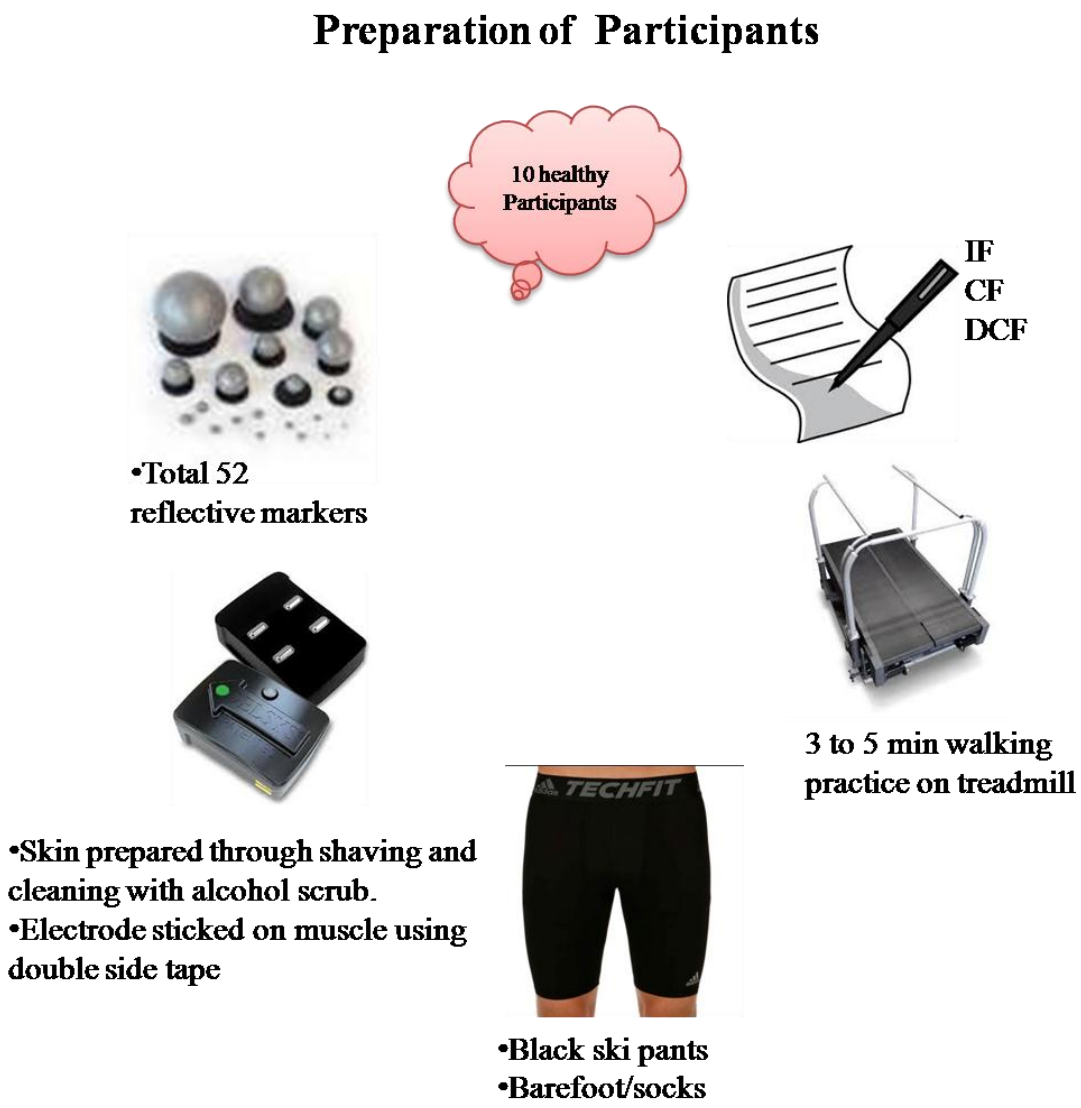


Figure 5.2 Preparation of the participants for data collection.
IF = Information form, CF = Consent form and DCF = Data collection form

Step 1: The participant was allowed to walk forward and backward on the ground for three minutes and then walking on treadmill five minutes at a self-selected speed before the start of the formal data collection to get accustomed to the procedure.

Step 2: The participant was barefoot or allowed to wear socks, and wore tight black ski pants and a sports bra (female). Participants who suffered from excessive sweating were allowed to wear socks to walk on the treadmill. To secure the exact placement of markers double-sided tape were used. Double sided tape was put on the feet marker placement areas, where after socks were put on. Another piece of double sided tape was put on top of the sock at exactly the

same place as the original spot. This method was used to avoid sweating to interfere with proper marker placement. Once the electrode placements were identified, the skin was prepared through shave and cleaning with an alcohol scrub. A Nup-rep gel was put onto the skin to ensure that the surface electrodes stick better to the skin before the start of EMG activity. Thirty-two individual light reflective markers were placed on anatomic landmarks (Figure 5.3).

Placement of marker set is shown in Figure 5.3 a & b

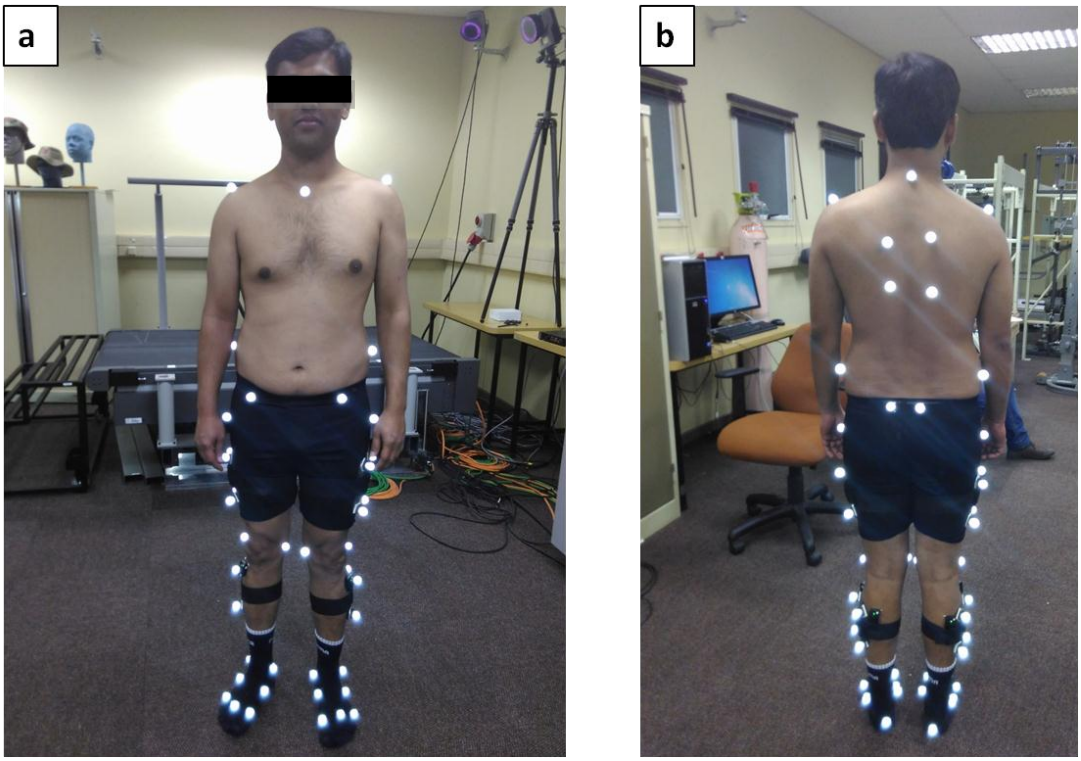


Figure 5.3 (a) Anterior and (b) posterior view of the participant with marker set.

Five tracking marker sets, each containing four markers, were positioned in the middle of the upper trunk, bilaterally on shank and thigh to pre-determined anatomical landmarks before the start of the kinematic data analysis. In total, 52 reflective markers were visible in the static pose. Before walking, two medial knee reflective markers were removed, because these reference markers were only required to calculate the width of the knee joint and to develop a segment in a static trial. Static pose: the participant stood in an erect position on the treadmill with 90 degrees of arm abduction so that all markers were visible, where after 5seconds of pose, data were captured.

Step 3: At the time when the speed was increased, the participant was allowed to hold the treadmill handrails. Data were captured for 10 to 15 seconds with 3 to 5 complete gait cycle when participant walked comfortably without using the handrails.

Step 4: In total, each participant was required to complete 18 trials at three levels of inclination and speed in both FW and BW. Manual drawing lots were used for random allocation of walking trial sequence. Participants were asked to perform 20 to 30 minutes of FW and BW on a treadmill at -5% (-2.8°), 0%, +5% (2.8°) levels of inclination and 0.28m/s (1km/h), 0.69m/s (2.5km/h) and 1.11m/s (4km/h) speed for each treadmill inclination level (Figure 5.1). The inclination angle, in degrees, was calculated from the percentage slope by the following equation.

$$\text{Angle}^{o} = (\arctan [\% \text{ slope}/100] \times 180/\pi)^{o}$$

In this research, the inclinations [level walking (0%), downhill walking (-5%), uphill walking (+5%)] and speeds [slow (0.28m/s), medium (0.69m/s), fast (1.11m/s)] were represented by percentage and m/s respectively.

5.3.10.2 Simulation procedure

Collected data were imported into Visual3D software to build the model and process the data. The processed data was simulated via OpenSim software to analyse the muscle activity. Detailed procedures are given in section 5.3.10.2.1 and 5.3.10.2.2

5.3.10.2.1Visual3D

Visual3D is a biomechanical modelling tool for 3D motion capture data analysis and modelling. It also gives the option to export OpenSim compatible motion files designed for OpenSim gait models with the following steps:

Step 1: Force data processing - the force data processing is shown in Figure 5.4 a & b

In Visual3D the minimum force platform threshold signal was set to 5Nmm to remove noise from the force signals. All analog force signals were filtered by a 12th order low-pass Butterworth filter with cut-off frequency of 25Hz

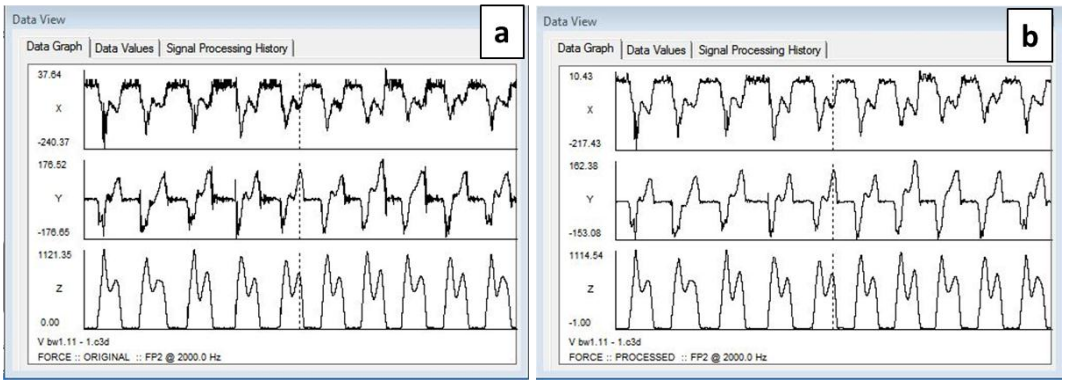


Figure 5.4 (a) Raw and (b) processed force data.

The raw signal sent through 12th order low-pass Butterworth filter with cutoff frequency of 25Hz. The X, Y, Z represents the amplitude of the signal from the corresponding axis

Step 2: Anthropometry model development with inverse kinematics

The static pose marker set data was imported to the workspace in Visual3D as shown in Figure 5.5 a & b.

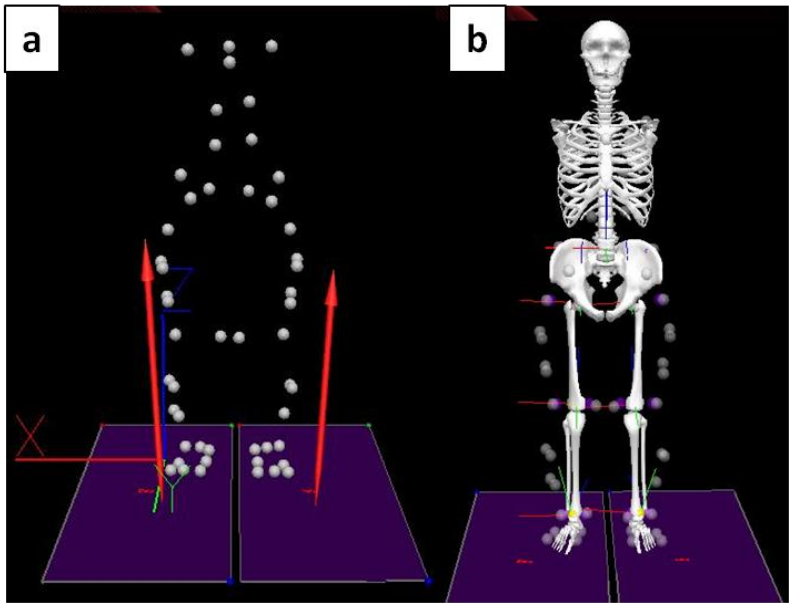


Figure 5.5 (a) static pose marker set and (b) static pose marker set with a hybrid anthropometry model.

The red axis represents the ground reaction force, the X, Y, Z represents the lab coordinate and two purple color boxes represent the force plate (screen grab from Visual3D)

A hybrid anthropometry model was built with segments, such as right foot, right shank, right thigh, left foot, left shank, left thigh, pelvis, and trunk. The trunk consists of abdomen, thorax, and head. The snapshot of the dynamic Visual3D model for before and after inverse kinematics (IK) is shown in Figure 5.6.

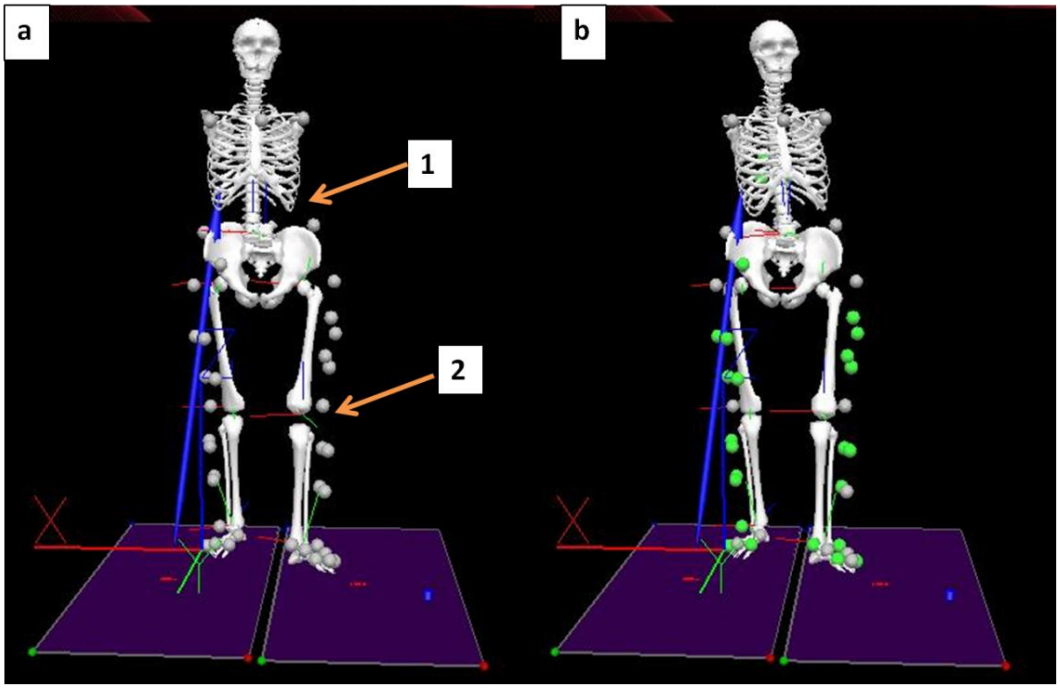


Figure 5.6 Visual3D developed an anthropometric model (a) without inverse kinematics and (b) with applied inverse kinematics.

In model (a) arrow 1 shows the misalignment of pelvis and thorax segments; arrow 2 shows more gaps between the knee joint segments. In the model (b) with applied inverse kinematics, the segments are connected well; the tracking markers are shown in green and the vertical blue axis represents ground reaction force (screen grab from Visual3D)

The developed model was assigned with motion data file. The coordinates were implemented with +Y as the walking direction. The IK was applied with Levenberg-Marquardt optimisation. Here, IK execution helps to minimise the difference between the experimental data and position of the model. It results in well-connected segments with constrained relative motion in the walking model.

Step 3: EMG data processing- EMG data filtering steps are shown in Figure 5.7

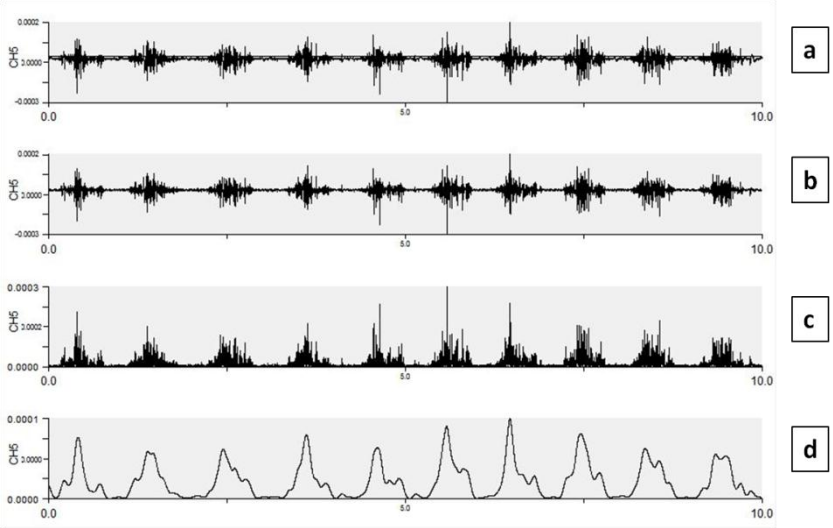


Figure 5.7 Steps followed for EMG signal processing: a) Raw EMG pass through (b) High-pass filter (c) Rectifier and (d) Low-pass filter.

The EMG signal was processed in three steps. The raw EMG signals typically have frequency content between 50 to 500 Hz (Figure 5.7a). Direct current bias in the signal was filtered by a 10th order high-pass Butterworth filter with cut-off frequency of 20Hz (Figure 5.7b). The implementation of rectification removed the negative value of the signal (Figure 5.7c). The rectified signal was finally sent through a 4^{th}order low-pass Butterworth filter with cut off frequency of 25 Hz. These processing steps yielded a well-defined and noise free EMG signal as shown in Figure 5.7d.

Step 4: Creation of OpenSim executable file

The method to create OpenSim executable *.mot files is shown as a flowchart in Figure 5.8.

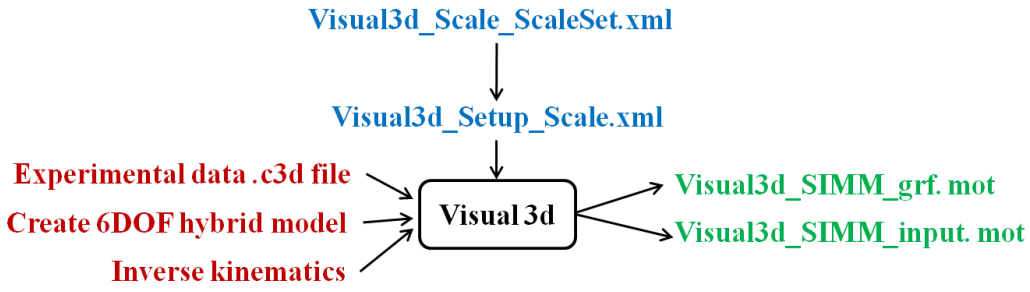


Figure 5.8 Input, output and setup files for simulation in OpenSim.

Input files are shown in red (left); setting files are shown in blue (top) and output files are shown in green (right).

The experimental motion data were imported from Qualisys track manager software as a *.c3d file. A set of Visual3D setup files was downloaded from the website (http://www.c-motion.com/v3dwiki/index.php/OpenSim). Among these files, two *.xml files were used while implementing in Visual3D to exporting OpenSim motion. The implementation gives two output files: Visual3D_SIMM_input.mot and Visual3D_SIMM_grf.mot files. The usage of these two files in OpenSim will be discussed in next section.

5.3.10.2.2 OpenSim

OpenSim is an open source software package that enables one to build, exchange and analyse computer models of the musculoskeletal system and dynamic simulations of movement (122). One of the major goals of the OpenSim project is to provide a common platform for creating and sharing models of the musculoskeletal system. An OpenSim model represents the dynamics of a system of rigid bodies and joints that are acted upon by forces to produce motion. The OpenSim model file is made up of components corresponding to parts of the physical system. These parts include bodies, joints, forces, constraints, and controllers.

In this study, a generic musculoskeletal model (gait2392_simbody.osim) developed by Delp et al (126) was selected to visualise the human walking and to analyse the functional capacity of the muscle. This model consists of 23 degrees of freedom and 92 muscle-tendon actuators. To simulate the musculoskeletal system with experimental data, an OpenSim dedicated workflow was used. The simulation procedure consists of four steps: 1) Scaling, 2) Load experimental motion data with a scaled model, 3) Residual Reduction Algorithm (RRA) and 4) Computed Muscle Control (CMC).

1. Scaling – steps are shown in Figure 5.9 flow chart

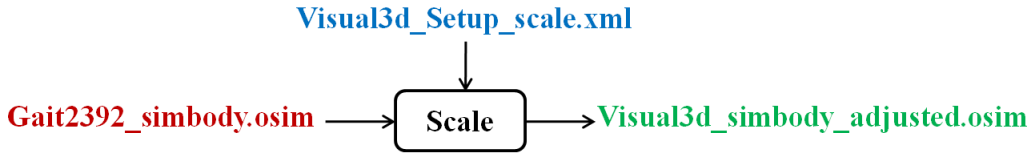


Figure 5.9 Input and output files of the scale tool.
Input files are shown in red (left); setting files are shown in blue (top) the input and output files are shown in green (right).

In the OpenSim graphical user interface, the generic musculoskeletal model (gait2392_simbody.osim) was scaled with height and weight of each individual participant. The

execution of scaling with Visual3D setup scale.xml enables one to alter the anthropometry of a model and matches with particular participants as closely as possible.

Figure 5.10 shows changes between the models.

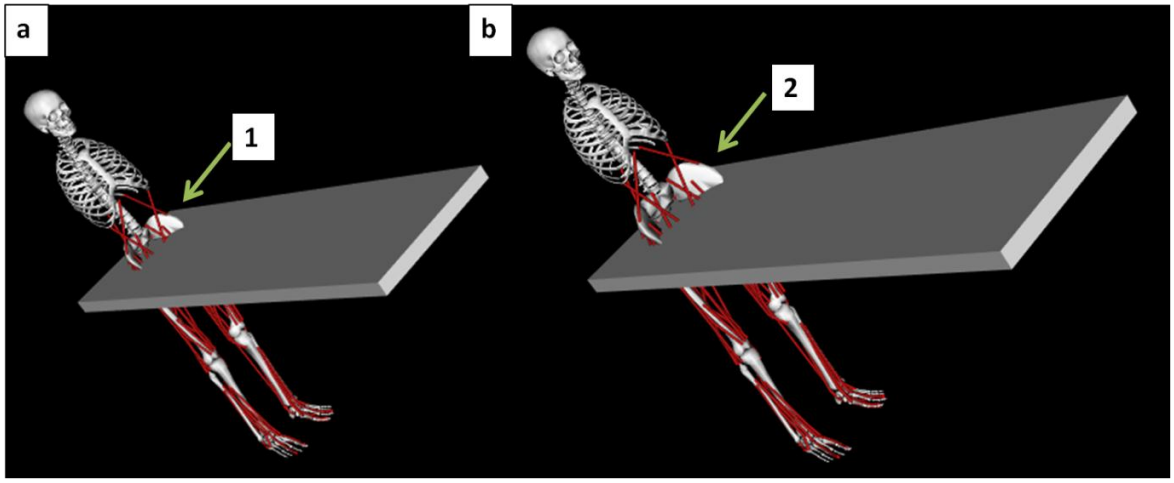


Figure 5.10 (a) The generic model and (b) participants-specific scaled model.
The green arrow 1 and 2 indicate that the pelvis size was changed from a generic model to a scaled model and the red color strings shows the actions of muscles

Scaling is typically performed by comparing experimental marker data to virtual markers placed on a model. Here, the position coordinates (x-y-z) were identified by marker locations from a static pose.

2. Loading of experimental motion data with a scaled model is shown in Figure 5.11

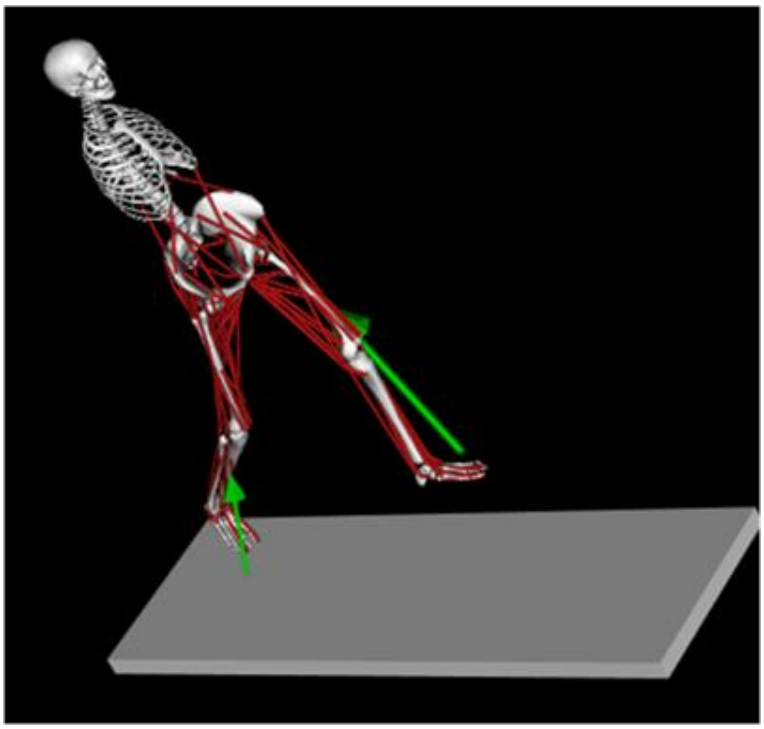


Figure 5.11 A scaled OpenSim model after being loaded the motion file.
The two green arrows represent the ground reaction force and the grey color box represents the force plate.

The *.mot file exported from Visual3D (section 5.1) was loaded with the scaled model. These files contain implemented IK and ground reaction force data. At this stage, the model was considered ready for simulation.

3. Residual Reduction Algorithm (RRA) workflow processes are shown in Figure 5.12 flow chart.

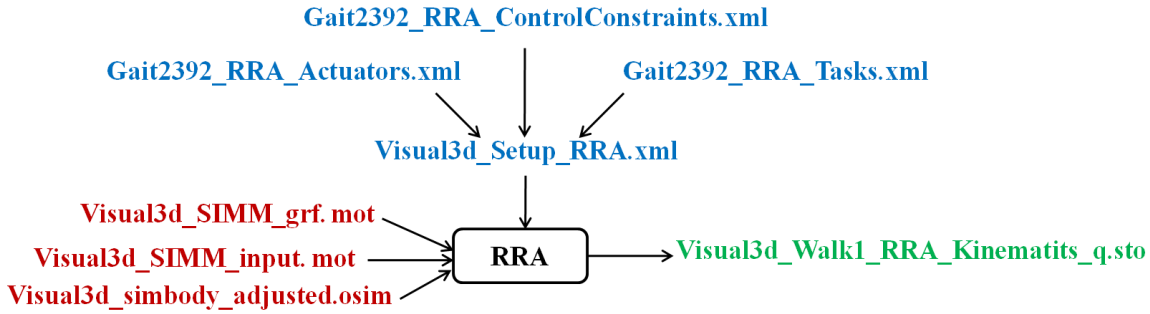


Figure 5.12 The flowchart shows the input files, shown in red (left); setting files are shown in blue (top) and output files are shown in green (right) during RRA execution.

The first step of simulation starts with RRA. As the name implies, RRA is intended to minimise the amount of residual force ($\overline{F}$ residual). It is more dynamically consistent with the measured ground reaction force and moment. The present models do not have enough musculature in the foot to allow the model to generate the appropriate joint torques. In order to improve the accuracy of the simulation, the subtalar and meta-tarso phalangeal joints were locked in the model before executing RRA.

RRA execution in OpenSim is shown in Figure 5.13

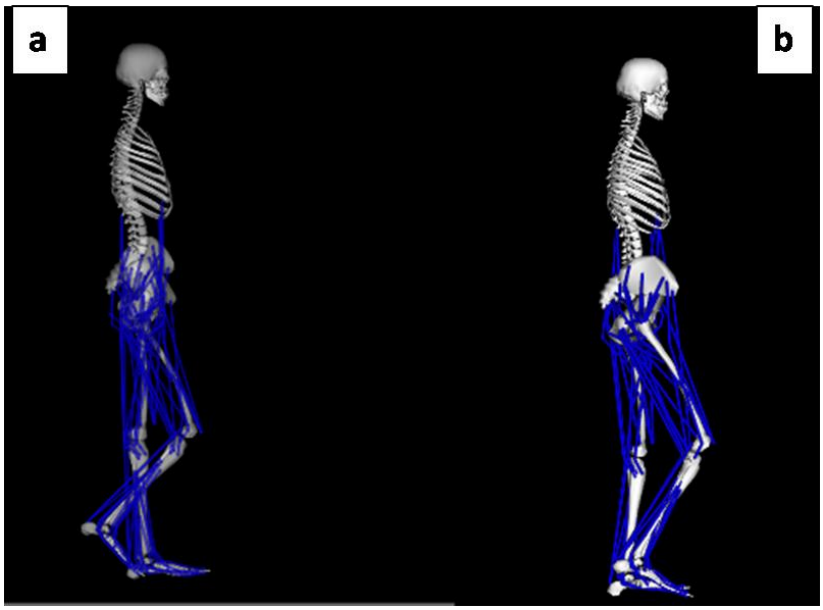


Figure5.13 The models: a) before and b) after RRA execution in OpenSim.

Residual forces go to zero as the amount of experimental and modelling errors approaches zero. In practice, this is never the case. The changes of the motion trajectories were checked using the RRA best practice and troubleshooting was recommended (122)to evaluate the results. Table5.1 shows threshold value recommended by OpenSim for the evaluation of RRA for over-ground walking. Value for treadmill walking in different inclination and speed are expected to be higher due to the increased difficulty of treadmill walking. Table 5.1 was utilised as a guideline for interpretation of results.

Table 5.1 Threshold value recommended by OpenSim for the evaluation of RRA results (Delp et al)**(122)**

Thresholds:	GOOD	OKAY	BAD
MAX Residual Force (N)	0-10 N	10-25N	> 25 N
RMS Residual Force (N)	0-5 N	5-10 N	> 10 N
MAX Residual Moment (Nm)	0-50 Nm	50-75 Nm	>75 Nm
RMS Residual Moment (Nm)	0-30 Nm	30-50 Nm	>50 Nm
MAX pErr (trans, cm)	0-2 cm	2-5 cm	>5 cm
RMS pErr (trans, cm)	0-2 cm	2-4 cm	>4 cm
MAX pErr (rot, deg)	0-2 deg	2-5 deg	> 5 deg
RMS pErr (rot, deg)	0-2 deg	2-5 deg	> 5 deg

4. Computed Muscle Control (CMC) workflow processes are shown in Figure 5.14.

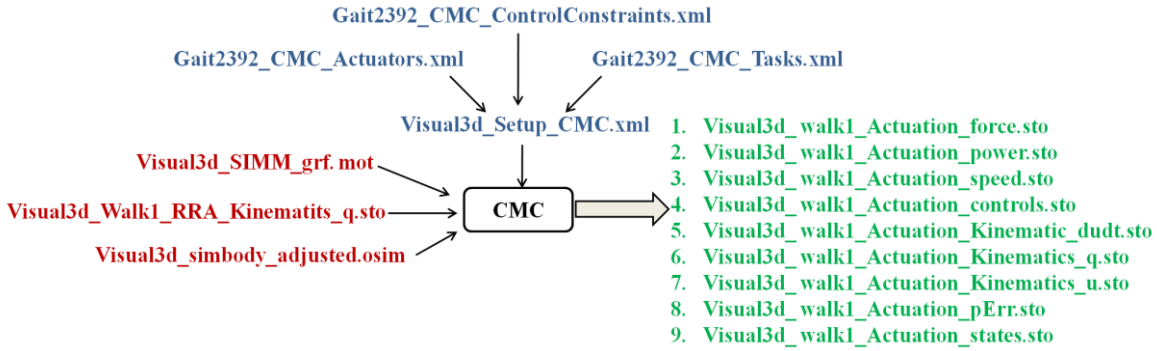


Figure 5.14 The flowchart shows the input files (red), setting files (blue) and output files (green) during CMC execution.

The final step is computed muscle controls (CMC); muscle excitation levels and individual muscle force which was calculated via CMC. The CMC produces a coordinated muscle – driven simulation towards a desired participant's kinematic trajectory.

The snapshot (Figure 5.15) from the CMC result shows the muscle activity in a specific time.

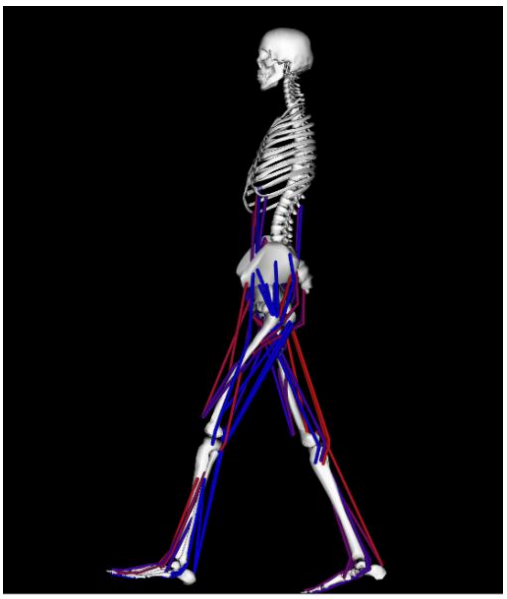


Figure 5.15 Dynamic muscle excitation calculated by CMC execution in OpenSim.
The blue and red strings represent inactive and active muscles at the particular phase of the gait cycle.

In a CMC algorithm force-length-velocity of the muscles, elastic properties of the muscles are accounted for by the contraction dynamics. During present simulation, the maximum excitation value of the control constrain were optimised to avoid error messages while executing CMC. The changes of the motion trajectories were checked with the CMC best practice and troubleshooting was implemented from the recommendations suggested by Delp et al (122) for evaluation of the results.

5.3.11 Simulation outputs and data analysis

The simulations provide a rich set of data from Visual3D and OpenSim. The procedure to extract the data and their analysis are presented in 5.3.11.1 & 5.3.11.2.

5.3.11.1 Visual3D data

The Visual3D provides advanced pipeline programmes to identify automatic gait events to calculate the gait properties. In this study, joint angle, joint power, joint moment and EMG were extracted for analysis. To compare kinetic parameters among different participants, the obtained data were normalised with participants-specific weight and height. The mean and standard deviation were obtained for a gait cycle among participants by Visual3D reports.

5.3.11.2 OpenSim data

In OpenSim, the final data were obtained from CMC results. The output files of CMC had three sets of data: joint kinematics, kinetics including muscle control and muscle state. Though OpenSim is a powerful tool to obtain additional information, the analysis has to be done manually. In this study, the necessary data were extracted from the respective output file and plotted separately for analysis.

5.3.11.3 Gait analysis

Each phase of the gait cycle is represented Figure 5.16

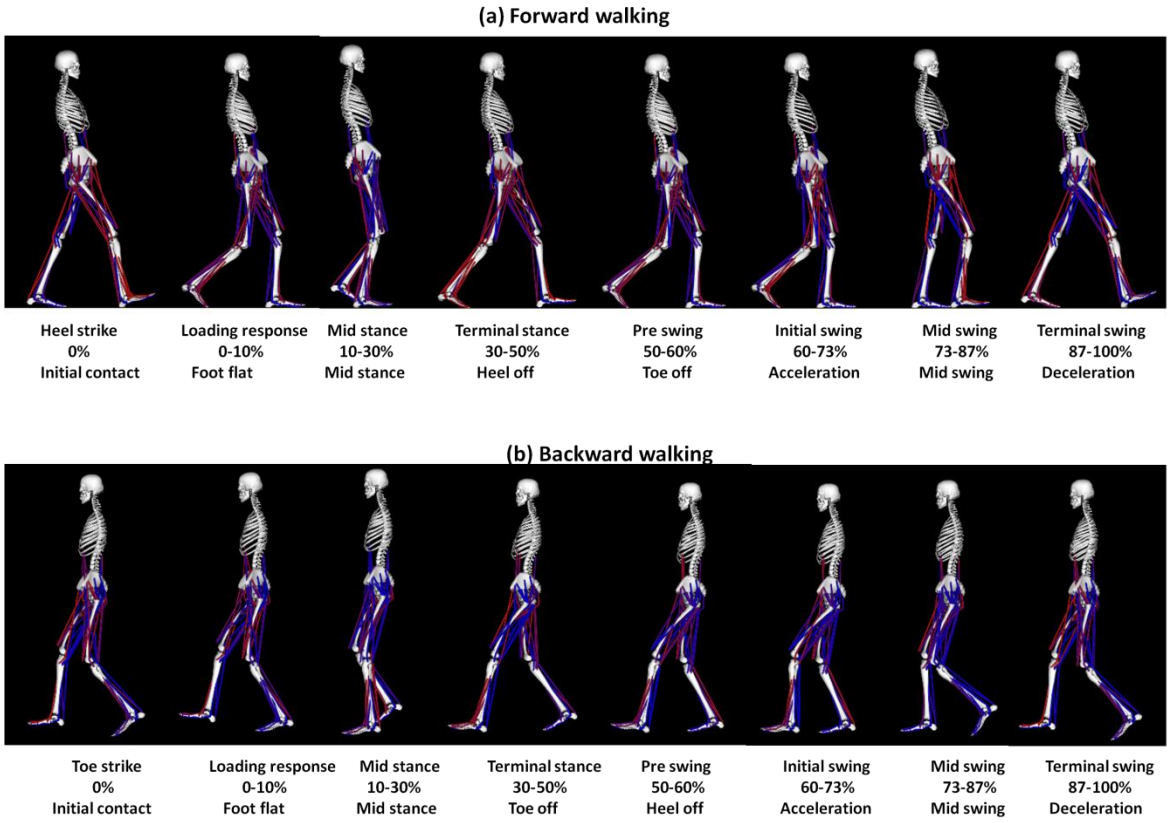


Figure 5.16 Each phase of the gait cycle was captured after executing CMC in OpenSim simulation.

Figure (a) simulation starts at right foot contact and ends at subsequent right foot contact. Figure (b) simulation starts at left foot contact and ends at subsequent left foot contact. Muscle color indicates simulated activation level from fully activated (red) to fully deactivated (blue)

The FW gait cycle for the present study was defined as from right heel strike to right heel strike (0-100%) as shown in Figure 5.16a. The BW gait cycle was defined as from left toe strike to left toe strike (0-100%) as shown in Figure 5.16 b. To quantify the contribution of the kinematic, kinetics and individual muscles during FW and BW, participants-specific simulation for both

conditions were generated. For FW each simulation started with ipsilateral heel contact and ended just before the next heel contact of same leg. For BW, simulation started with ipsilateral toe-contact and ended just before the next toe-contact of same leg. However, all BW data were time-reversed to equalise the contact position as well as the type of event.

5.3.11.4 Data reduction

The mechanical power is evaluated mathematically to obtain generation and absorption of power at lower limb joints (171). The joint power data for the hip, knee, and ankle were individually integrated with respect to time over discrete periods of positive and negative power. The integrated positive power was an indication of power generation and negative power and an indication of power absorption at the specific joint (171).

5.3.11.5 Statistical analysis

All the data were time-normalised and are expressed as a 100% gait cycle. The kinematic data and the body weight normalised kinetic data (joint moment, joint power and muscle activity) collected from 10 participants were used to calculate the mean value. These mean value for each quantity were used for further statistical analysis. The correlation coefficient was calculated using Pearson's correlation (< 0.29 indicates low correlation, between 0.30 and 0.50 indicates moderate, and above 0.50 to 1 indicates high correlation). A one-way analysis of variance (ANOVA) with the Tukey post hoc test was used to detect significant differences between: a) FW group (different inclinations and speeds); b) BW group (different inclinations and speeds); c) FW and BW (different inclinations and speeds). Statistical significance was set at $p < 0.05$ and $p < 0.001$.

5.4 Results

The results section is outlined according to the objectives of this study which are:

5.4.1 to determine the biomechanical characteristics of FW at three respective inclinations (0%, -5%, +5%) and three respective speeds (0.28m/s, 0.69m/s and 1.11m/s).

5.4.2 to determine the biomechanical characteristics of BW at three respective inclinations (0%, -5%, +5%) and three respective speeds (0.28m/s, 0.69m/s and 1.11m/s).

5.4.3 to compare the biomechanical characteristics of FW and BW at three respective inclinations (0%, -5%, +5%) inclinations and three respective speeds (0.28m/s, 0.69m/s and 1.11m/s).

Ten participants who fulfilled the inclusion criteria were included in the study after this researcher obtained their informed consent. They included seven males and three females with a mean age of 32.8±2.85 years, a mean height of 168.2±9.06 cm and a mean weight of 71.62±13.6 kg.

5.4.1 Kinematics and kinetics of FW at the three respective levels of inclination and speed

The results for the first objective of this chapter, which refers to the investigation into the kinematics and kinetics of FW at the three levels of inclination and the three various speed, are presented in this section.

5.4.1.1 Forward walking: temporal and spatial parameters

Table 5.2 presents the temporal and spatial parameters of FW for level surface walking (0%) *versus* inclined surface walking (-5% & +5%) at various speed

Table 5.2 The calculated mean and standard deviation for temporal and spatial gait parameters during FW at three levels of inclination and speed.

Temporal and Spatial Parameters	**FW Inclination**	**0.28 (m/s)**		**0.69 (m/s)**		**1.11 (m/s)**	
		Mean	SD	Mean	SD	Mean	SD
Gait cycle time (seconds)	0%	1.87	0.32	1.26	0.15	1.05	0.12
	-5%	1.61	0.16	1.2	0.11	1.02	0.12
	+5%	1.73	0.28	1.28	0.14	1.06	0.1
Step time (seconds)	0%	0.95	0.2	0.62	0.07	0.51	0.06
	-5%	0.77	0.07	0.56	0.05	0.49	0.07
	+5%	0.85	0.13	0.65	0.07	0.54	0.05
DLS (meter)	0%	1.04	0.28	0.47	0.08	0.31	0.08
	-5%	0.81	0.15	0.42	0.05	0.27	0.04
	+5%	0.97	0.22	0.45	0.05	0.3	0.05
Step length (meter)	0%	0.27	0.04	0.42	0.05	0.58	0.07
	-5%	0.18	0.04	0.37	0.04	0.52	0.09
	+5%	0.23	0.05	0.45	0.04	0.59	0.06

SD – standard deviation; DLS – double limb support

The temporal parameters for FW such as gait cycle time, step time and DLS declined with an increase in speed for all the inclination. Under these same conditions, the spatial parameter of step length was increased.

5.4.1.2 Forward walking: joint kinematics

In this section, the lower limb joint angles for hip, knee, and ankle joint were analysed for FW. Figure 5.17 presents the joint angles, regulated by speed and inclination, for each of the 100% gait cycle, while Table 5.3 shows the statistical comparison.

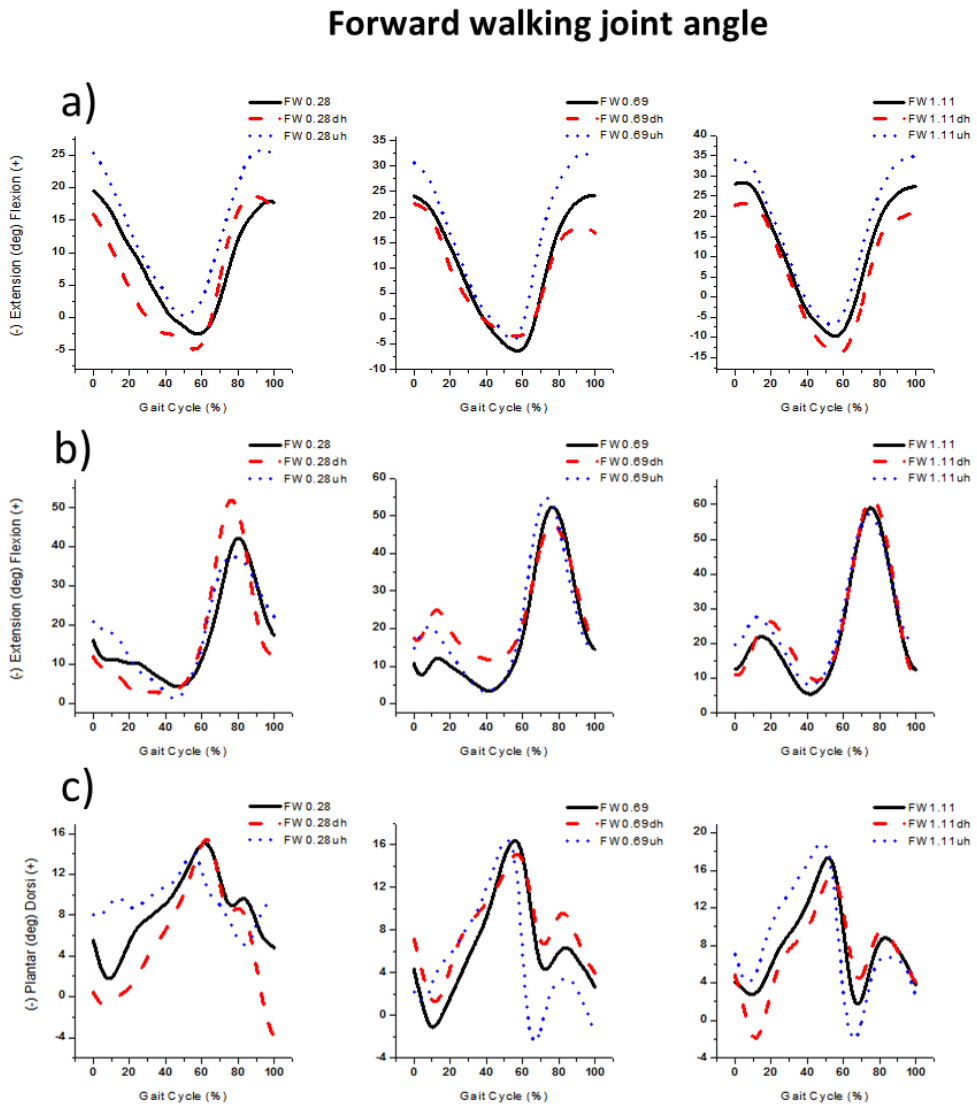


Figure 5.17 Comparison of the angle patterns for the a) hip, b) knee, and c) ankle joints during the FW gait cycle for the three levels of inclination with respect to speed.

Solid black line: (0%), dh: downhill red dashed line (-5%) , uh: uphill blue dotted line (+5%)

The hip joint angle showed a similar pattern for all the inclinations and speeds shown in Figure 5.17a. Furthermore, the total range of motion (RoM) also increased for all inclinations with an increase in speed. In this study, the hip extension angle increased during downhill walking in contrast to uphill walking when the flexion angle increased.

As shown in Figure 5.17b, the knee joint angle also showed similar patterns for all inclinations and speeds. Depending upon the speed, the flexion angle of the knee joint in the stance phase showed variation (e.g. with increased speed (0.69m/s, 1.11m/s), the knee showed significant flexion in the heel strike to midstance phase than at a slow speed (0.28m/s)). In the swing phase, with an increase in speed, the total RoM increased for all inclinations.

The ankle joint angles showed similar patterns, with two dorsiflexion occurring at all of the inclinations and speeds (Figure 5.17c). In the intervals between the two dorsiflexion, the ankle showed a plantar flexion movement for fast speed on an uphill incline.

Statistical comparison of the joint angle for different inclinations at varying speeds during forward walking

Table 5.3 presents comparison of the joint angles for FW on a level surface (0%) *versus* downhill walking (-5%); FW on a level surface (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%), all at varying speeds. The one-way ANOVA p-value was used to calculate the significance of the difference between joint angle at all of the inclination and at each speed. In this study, $p < 0.05$ and $p < 0.001$ pointed to a statistically significant difference between the gait cycles. The correlation coefficient (r-value) was calculated to establish the relationship between joint angle at the various inclinations and at each speed.

Table 5.3 Comparison of the joint angles during forward walking for the respective inclinations at each speed.

Joint angle (deg)	FW Speed (m/s)	0%/ -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Hip	0.28	0.89	<0.001	0.95	<0.001	0.97	<0.001
	0.69	0.98	0.06	0.97	<0.001	0.96	<0.001
	1.11	0.99	<0.001	0.99	<0.001	0.97	<0.001
Knee	0.28	0.91	0.80	0.94	0.10	0.89	<0.05
	0.69	0.97	<0.001	0.95	<0.001	0.95	<0.001
	1.11	0.98	<0.05	0.99	<0.001	0.95	0.81
Ankle	0.28	0.95	<0.001	0.43	<0.001	0.37	<0.001
	0.69	0.97	<0.001	0.62	<0.001	0.58	<0.001
	1.11	0.88	<0.001	0.83	<0.05	0.52	<0.001

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

The hip, knee and ankle joint angles showed strong correlation at all of the compared inclinations and speeds during FW. The p-value for the joint angles at all of the compared inclinations and speeds were statistically significant except in the case of comparison between the knee joint angles in level surface walking to downhill walking at 0.28m/s, level surface walking to uphill walking at 0.28 m/s and downhill walking to uphill walking at 1.11m/s.

5.4.1.3 Forward walking: joint kinetics

Joint moment

In this section, lower limb joint moment for the hip, knee, and ankle joint respectively were analysed in the case of FW. Figure 5.18 presents the joint moment regulated by inclination and speeds, for each of the 100% gait cycle, while Table 5.4 shows the statistical comparison.

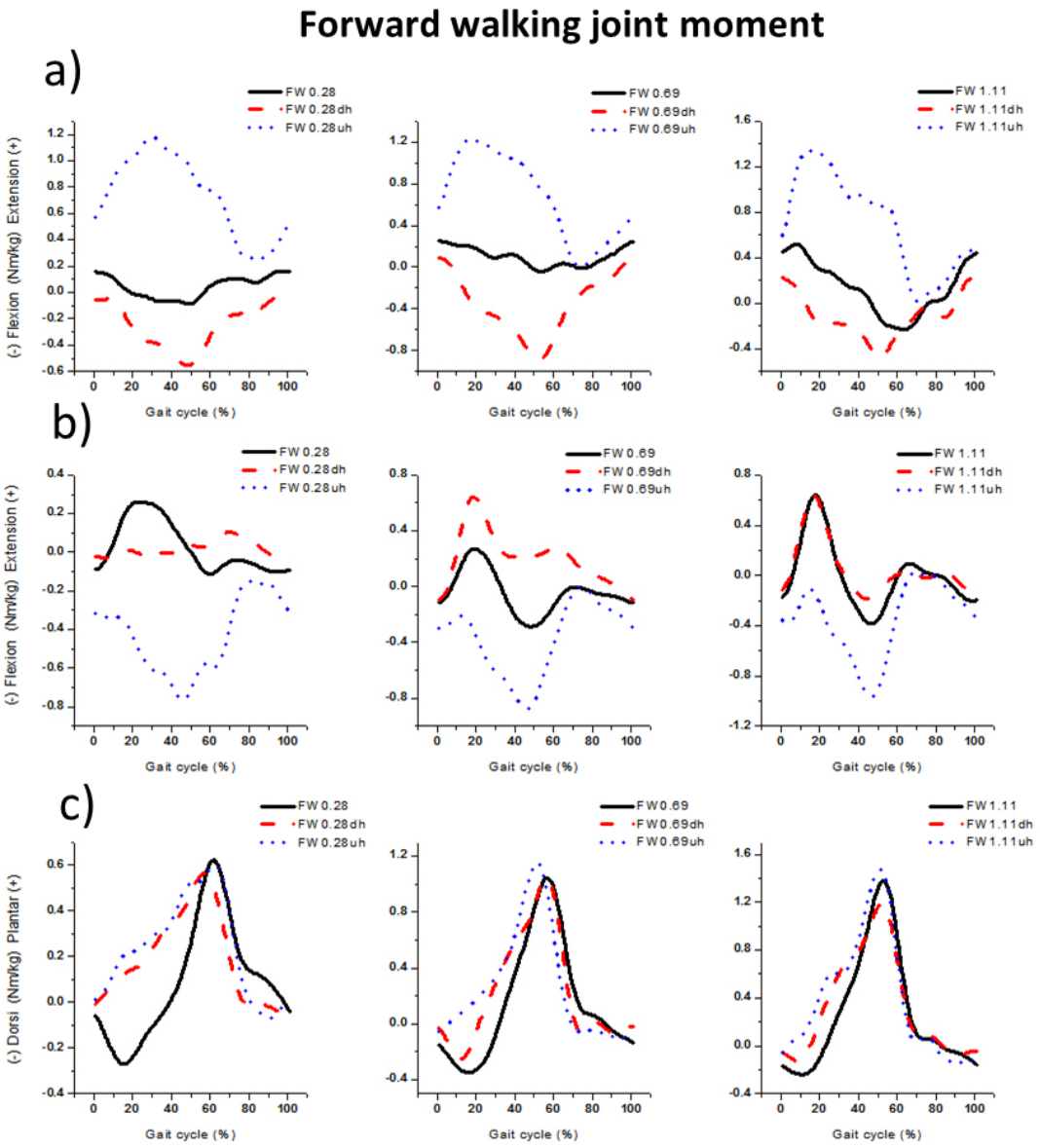


Figure 5.18 Comparison of the moment patterns for the a) hip, b) knee, and c) ankle joints during the FW gait cycle for the three levels of inclination with respect to speed.

Solid black line: (0%), dh: downhill red dashed line (-5%) , uh: uphill blue dotted line (+5%)

Figure 5.18a shows that the hip joint experienced an extensor moment during uphill walking, whereas these same joint experienced flexor moments at all speed during level and downhill walking.

The knee joint experienced a flexor moment at all speeds in uphill walking, whereas it experienced two extensors moment at all speeds during level and downhill walking. Figure 5.18b shows the nature of this flexor/extensor moment of the knee joints at different inclinations. These moment are opposite to those relating to the hip moment.

The ankle joint moment showed similar patterns for all inclinations and speeds. During the heel-strike to loading-response phase, it experienced dorsiflexor moment at all inclination, except in the cases of level and uphill walking at a speed of 0.28m/s. A plantar flexor moment was experienced from the mid-stance to the pre-swing phase, and its magnitude increased with respect to speed (Figure 5.18c).

Statistical comparison of joint moment for the respective inclinations at varying speed during forward walking

Table 5.4 presents comparison for the joint moment for forward level walking (0%) *versus* downhill walking (-5%); forward level walking (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%) at varying speed. The one-way ANOVA p-value was used to calculate the significance of the difference between joint moment at all of the inclinations and at each speed. In this study, $p < 0.05$ and $p < 0.001$ showed statistically significant differences between the gait cycles. The correlation coefficient (r-value) was calculated to establish the respective relationship between the joint moment and the respective inclinations at each speed.

Table 5.4 Comparison of the joint moment during forward walking for the respective inclinations at each speed.

Joint moment (Nm/kg)	FW Speed (m/s)	0% / -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Hip	0.28	0.94	<0.001	-0.77	<0.001	-0.67	<0.001
	0.69	0.68	<0.001	0.40	<0.001	-0.33	<0.001
	1.11	0.70	<0.001	0.48	<0.001	-0.20	<0.001
Knee	0.28	-0.33	0.88	-0.43	<0.001	0.05	<0.001
	0.69	0.60	<0.001	0.43	<0.001	-0.25	<0.001
	1.11	0.96	0.33	0.56	<0.001	0.38	<0.001
Ankle	0.28	0.56	<0.05	0.57	<0.001	0.95	0.29
	0.69	0.92	0.40	0.76	0.11	0.91	0.74
	1.11	0.94	0.63	0.90	0.14	0.97	0.60

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient "r" and the ANOVA "p" value.

The hip and knee joint moment showed negative correlation between uphill and downhill walking at all speeds. The first and second comparison showed mostly positive correlation between joint moment and all inclination at each speed. These statistical values were found to

be in line with the observed patterns shown in Figure 5.18. The p-value showed significantly difference in the joint moment at all compared inclinations and speeds except for the comparison between level and downhill walking in the case of the knee joint at the speed of 0.28m/s and 1.11m/s.

Ankle joint moment showed positive correlation for all of the inclinations at all of the speeds. The p-value showed a non-significant difference in the joint moment at all of the compared inclinations and speeds except for the comparison between level and downhill walking at 0.28m/s and between level and uphill walking at 0.69m/s.

Joint power

In this section, lower limb joint power for the hip, knee, and ankle joints respectively was analysed during FW. Figure 5.19 presents joint power, regulated by the speed of walking and the inclination of the surface in each of the 100% gait cycle, while Table 5.5 shows the statistical comparison.

In the case of uphill walking, the hip and knee joint showed both power generation and absorption at all speeds (Figures 5.19a and b). On the other hand, both downhill walking and level walking were found to generate less power than they absorb. In this study, downhill walking showed more power absorption than walking on a level surface. In both types of walking, greater magnitudes of power were found to be generated by the hip and knee joints by increasing the speeds.

Figure 5.19c shows similar ankle joint power patterns for the recorded inclinations and speeds. The ankle joint showed a significant generation of power from heel-off to mid-swing at all inclinations and speeds. In both types of walking, greater magnitudes of power were found to be generated by the ankle joint by increasing the speed.

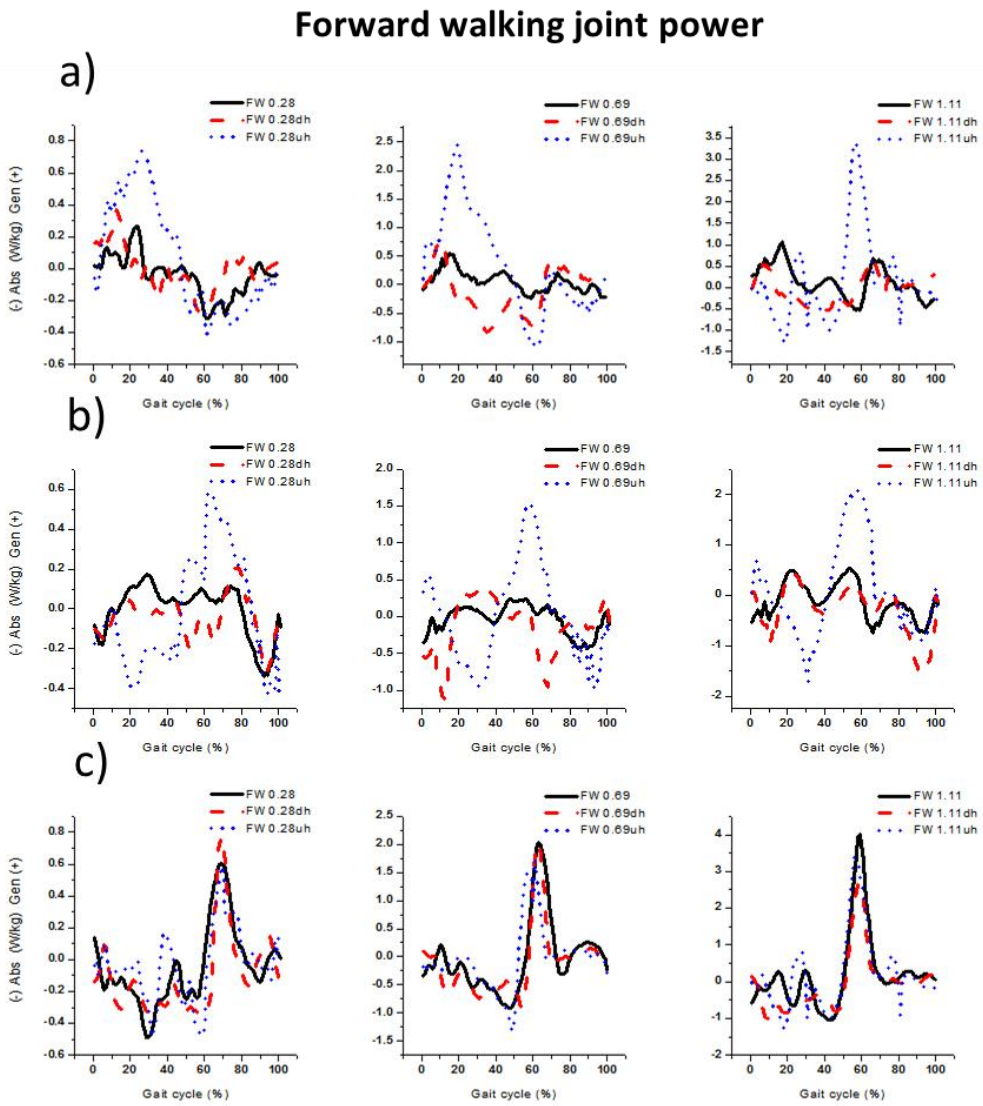


Figure 5.19 Comparison of the power patterns of the a) the hip, b) knee, and c) ankle joints during the FW gait cycle for the three levels of inclination with respect to speed.

Solid black line: (0%), dh: downhill red dasedh line (-5%), uh: uphill blue dotted line (+5%)

Statistical comparison of joint power for the three levels of inclination at varying speed during forward walking

Table 5.5 presents the comparison of joint power for forward level walking (0%) *versus* downhill walking (-5%); forward level walking (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%) at varying speed. The one-way ANOVA p-value was used to calculate the significance of the difference between joint power at all of the three inclinations at each speed. In this study, $p < 0.05$ and $p < 0.001$ showed a statistically significant difference between the gait cycles. The correlation coefficient (r value) was calculated to establish the relationship between joint power and the respective inclinations at each speed.

Table 5.5 Comparison of joint power during forward walking for the respective inclinations at each speed.

Joint power (W/kg)	FW Speed (m/s)	0% / -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Hip	0.28	0.42	0.51	0.73	<0.05	0.33	<0.001
	0.69	0.19	0.10	0.78	<0.001	0.01	<0.001
	1.11	0.22	0.18	-0.54	0.88	0.07	0.07
Knee	0.28	0.57	0.34	0.29	0.82	0.20	0.69
	0.69	0.19	0.29	0.38	0.72	-0.34	0.06
	1.11	0.73	0.10	0.26	0.12	0.31	0.12
Ankle	0.28	0.78	0.31	0.75	0.83	0.74	0.11
	0.69	0.88	0.37	0.66	0.98	0.56	0.47
	1.11	0.90	0.11	0.85	0.95	0.86	0.20

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient "r" and the ANOVA "p" value.

The power patterns of the ankle joint were found to be strongly correlated with non-significant difference between joint power at the compared inclinations and speeds. This shows that the ankle patterns reflected both linear relationship and indifferent mean power value. Unlike the case of the ankle, the power requirements for the hip and knee at each phase in the gait cycle were found to differ with respect to inclination. This can be seen from the varying correlation coefficient value when comparing the joint power of the hip and knee in terms of the various inclinations.

Muscle activity

Among 92 simulated muscles in the anthrometric model, seven keymuscles were selected for studying the hip, knee and ankle joints.The activitylevels of three hip joint muscles (the gluteus maximus, the gluteus medius, and the iliacus), two biarticular muscles used in both the hip and knee joints (the rectus femoris and the biceps femoris), and two ankle jointmuscles (the tibialis anterior and the lateral gastrocnemius) were plotted for analysis. Figures 5.20 to 5.22 present the activity levels of these muscles which are influenced by the variables of speeds and inclination while Table 5.6 shows the statistical comparison.

Hip joint muscles: Figure 5.20 shows the activity levels of the gluteus maximus, gluteus medius and iliacus muscles during FW in terms of the three selected inclinations with respect to speeds.

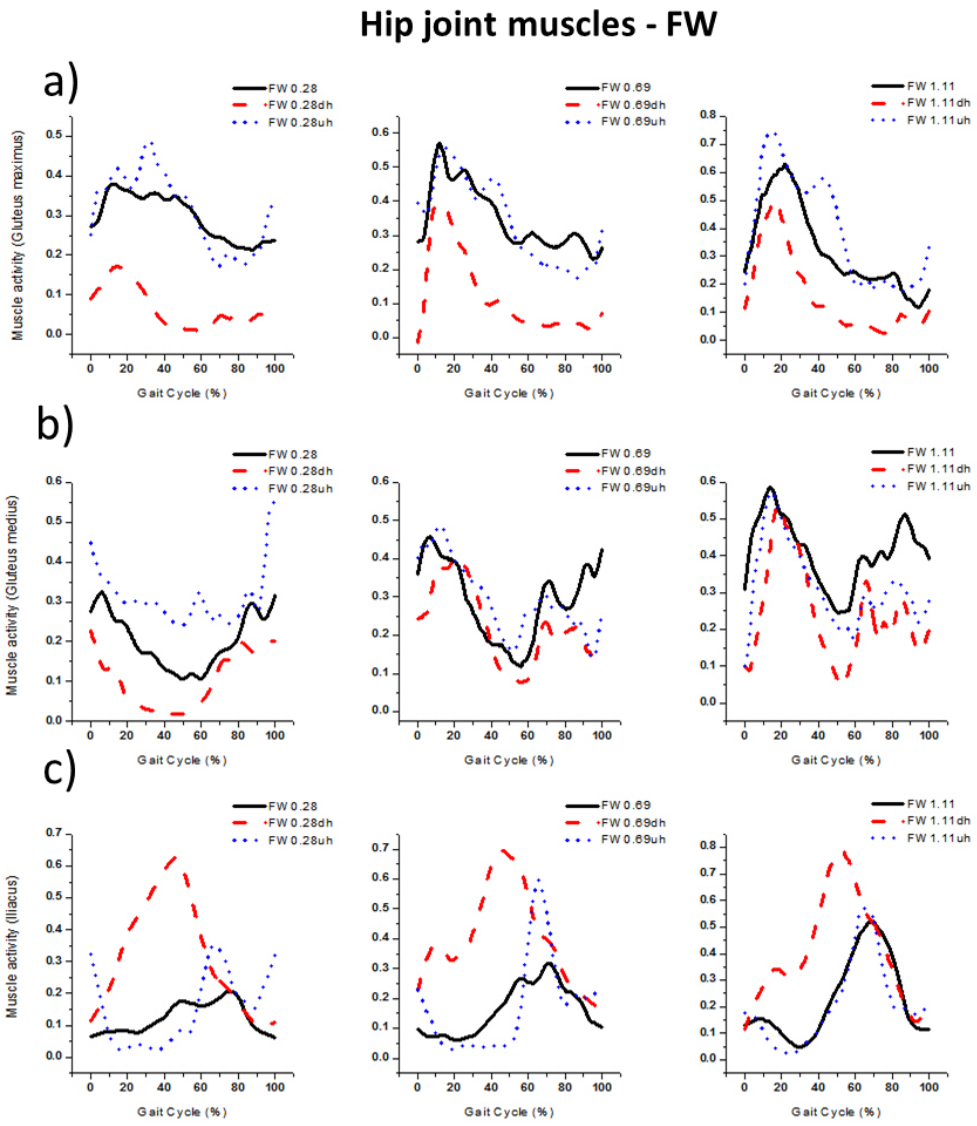


Figure 5.20 Comparison of the activity levels of the a) gluteus maximus, b) gluteus medius and c) iliacus muscles during the FW gait cycle for the three levels of inclination with respect to speed.

Solid black line: (0%), dh: downhill; red dashed line (-5%), uh: uphill; blue dotted line (+5%)

The activity levels of the gluteus maximus (GM) muscle (Figure 5.20a) showed similarities in respect of varying magnitudes at all inclinations and speeds. The high level of muscle activity from the heel strike to the mid-stance phase gradually declined up to the swing phase.

The activity levels of the gluteus medius (Gmed) muscle (Figure 5.20b) showed similarities for all inclinations at each of the three speeds. The magnitude of muscle activity was found to vary

depending on the three respective inclinations. Reduced Gmed activity was found during the pre-swing phase of a gait cycle.

Inclination caused the activity levels of the iliacus (IL) muscle to vary (Figure 5.20c). Downhill walking, for instance, caused a higher magnitude of muscle activity. Greater IL activity was found during the mid-stance to terminal-swing phase in level and uphill walking. The IL muscle was found to be active for an entire gait cycle at all speeds during downhill walking.

Biarticular muscles of the hip and knee joints: Figure 5.21 presents comparison during FW of the activity levels of the rectus femoris and biceps femoris muscles for the three respective inclinations with respect to speeds.

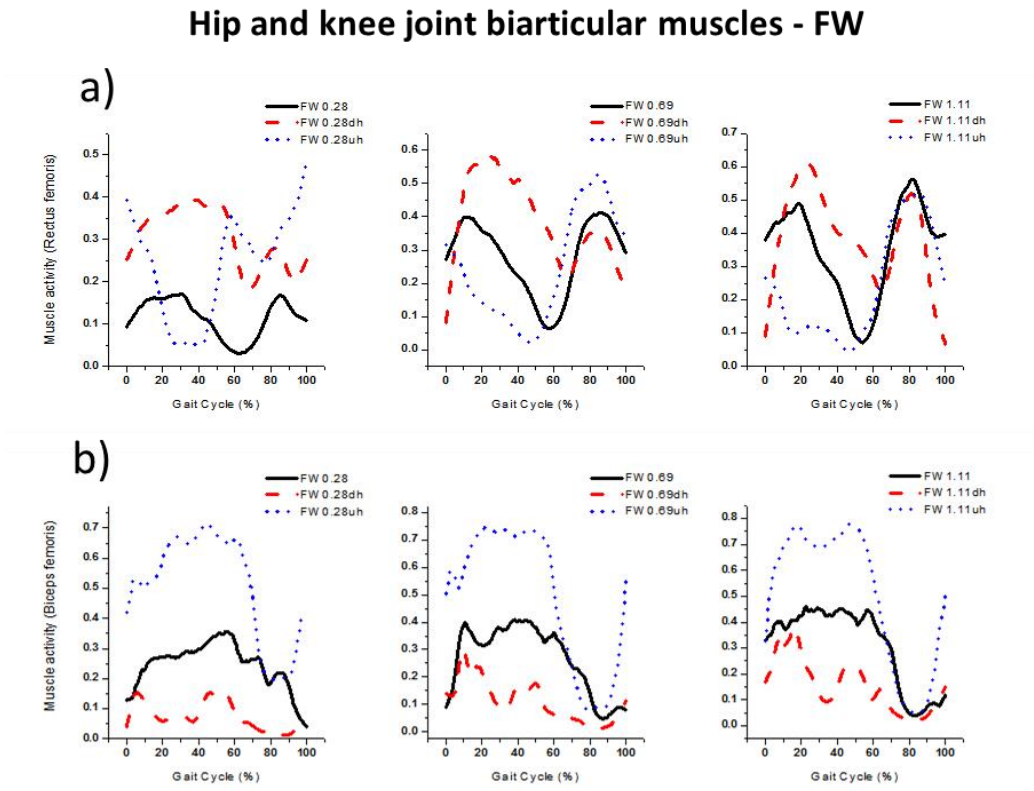


Figure 5.21 Comparison of the activity levels of the a) rectus femoris and b) biceps femoris muscles during the FW gait cycle for the three levels of inclination with respect to speed.
Solid black line: (0%), dh: downhill red dashed line (-5%) , uh: uphill blue dotted line (+5%)

The rectus femoris (RF) muscle activity levels (Figure 5.21a) were found to differ according to inclination. A higher magnitude of muscle activity was seen in downhill walking. Greater activity was found to occur in the RF muscle during the entire stance phase rather than during

the swing phase in level and downhill walking. During uphill walking, the RF muscle was found to be active during the heel-strike and swing phases of the gait cycle at all speeds.

The activity levels of the biceps femoris (BF) muscle (Figure 5.21b) were similar at all speeds. In contrast to the activity levels of the RF muscle, a higher magnitude of muscle activity was seen in uphill walking. This behaviour in the BF muscle is directly opposed to that in the RF muscle. Greater activity was found in the BF muscle during the heel-strike to mid-swing phase of the gait cycle at all inclinations, while these muscles showed the least activity in downhill walking at all speeds.

Ankle joint muscles: Figure 5.22 shows comparison of the activity levels of the tibialis anterior and lateral gastrocnemius muscles during FW for the three selected inclinations with respect to speeds.

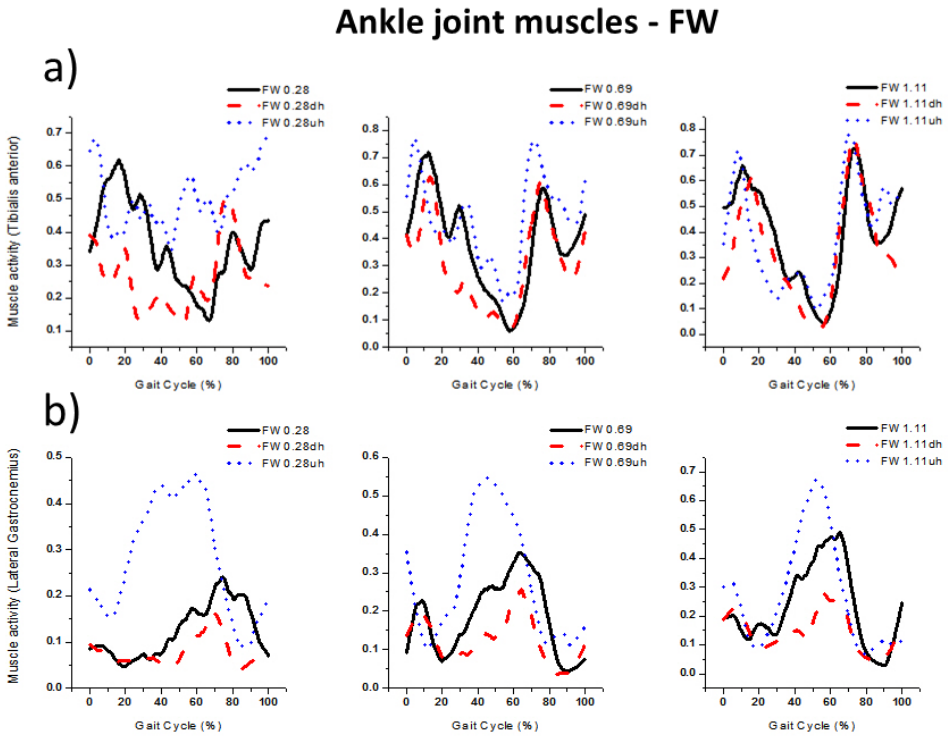


Figure 5.22 Comparison of the activity levels of the a) tibialis anterior and b) lateral gastrocnemius muscles during the FW gait cycle for the three levels of inclination with respect to speed

Solid black line: (0%), dh: downhill red dashed line (-5%) , uh: uphill blue dotted line (+5%)

The activity levels of the tibialis anterior (TA) muscle (Figure 5.22a) proved to be similar at all speeds. There were two peak activity levels, one in the loading-response phase and the other in the pre-swing phase at all of the selected inclinations and speeds.

The activity levels of the lateral gastrocnemius (LGas) muscle (Figure 5.22b) were found to change in association with inclination. A greater magnitude of muscle activity was seen in uphill walking. Greater activity in the LGas muscle was found during the loading-response to the terminal-swing phase at all of the selected inclinations. In terms of the inclination variable, the LGas muscle showed the smallest magnitude of activity during downhill walking.

Statistical comparison of muscle activity for the respective inclinations at varying speed during forward walking

Table 5.6 presents comparison of muscle activity for FW on a level surface (0%) *versus* downhill walking (-5%); forward level walking (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%) at varying speed.

Table 5.6 Comparison of muscle activity during forward walking for the respective inclinations at each speed.

Muscle activity	FW Speed (m/s)	0% / -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Gluteus maximus	0.28	0.48	<0.001	0.89	<0.001	0.51	<0.001
	0.69	0.92	<0.001	0.87	<0.001	0.08	<0.001
	1.11	0.91	<0.001	0.87	<0.001	0.84	<0.001
Gluteus medius	0.28	0.78	<0.001	0.63	<0.001	0.50	<0.001
	0.69	0.66	<0.001	0.60	0.56	0.83	<0.001
	1.11	0.70	<0.001	0.78	<0.001	0.85	<0.001
Iliacus	0.28	0.22	<0.001	0.34	<0.001	-0.64	<0.001
	0.69	0.23	<0.001	0.69	0.12	-0.20	<0.001
	1.11	0.48	<0.001	0.91	<0.05	0.45	<0.001
Biceps femoris	0.28	0.45	<0.001	0.66	<0.001	0.70	<0.001
	0.69	0.58	<0.001	0.80	<0.001	0.72	<0.001
	1.11	0.65	<0.001	0.92	<0.001	0.77	<0.001
Rectus femoris	0.28	0.38	<0.001	-0.37	<0.001	-0.74	<0.001
	0.69	0.18	<0.001	0.53	<0.001	-0.62	<0.001
	1.11	0.33	<0.001	0.61	<0.001	-0.20	<0.001
Tibialis anterior	0.28	0.12	<0.001	-0.12	<0.001	0.18	<0.001
	0.69	0.83	<0.001	0.67	<0.001	0.76	<0.001
	1.11	0.86	<0.001	0.75	0.99	0.73	<0.001
Lateral Gastrocnemius	0.28	0.52	<0.001	-0.12	<0.001	0.30	<0.001
	0.69	0.80	<0.001	0.59	<0.001	0.41	<0.001
	1.11	0.80	<0.001	0.81	<0.001	0.67	<0.001

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

The pattern of muscle activity depends largely on the nature of burst. The statistical comparison of muscle activities for the respective inclinations show significant difference ($p < 0.05$ and $p < 0.001$) with the range of the correlation coefficient being $r = -0.74$ to 0.92. The muscles were found to be active in both concentric and eccentric contraction during the flexion and extension movements. During these activities, the shape, magnitude and duration of burst proved to be significantly different from that reflected in the p-value.

5.4.2 Kinematics and kinetics of BW at the three respective levels of inclination and speed

The results for the second objective of this chapter, which refers to the investigation of the kinematics and kinetics of BW for the three levels of inclination and speed, are presented in this section.

5.4.2.1 Backward walking: temporal and spatial parameters

Table 5.7 presents the temporal and spatial parameters of BW for the various levels of inclination and speed.

Table 5.7 The calculated mean and standard deviation for the temporal and spatial gait parameters during BW at the three levels of inclination and speed.

Temporal and Spatial Parameters	BW Inclination	0.28 (m/s)		0.69 (m/s)		1.11 (m/s)	
		Mean	SD	Mean	SD	Mean	SD
Gait cycle time (seconds)	0%	1.7	0.39	1.25	0.12	1.01	0.09
	-5%	1.84	0.33	1.23	0.08	1.02	0.11
	+5%	1.68	0.14	1.27	0.13	1.03	0.08
Step time (seconds)	0%	0.85	0.22	0.64	0.07	0.51	0.06
	-5%	0.97	0.21	0.62	0.06	0.51	0.06
	+5%	0.83	0.1	0.59	0.09	0.5	0.05
DLS (meter)	0%	0.83	0.26	0.45	0.07	0.29	0.07
	-5%	0.9	0.23	0.43	0.09	0.3	0.04
	+5%	0.81	0.15	0.41	0.05	0.28	0.03
Step length (meter)	0%	0.25	0.05	0.44	0.05	0.58	0.07
	-5%	0.28	0.05	0.44	0.04	0.58	0.04
	+5%	0.22	0.05	0.41	0.08	0.54	0.06

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s

The temporal parameters such as gait cycle time, step time and DLS declined with an increase in speed at all of the levels of inclination during BW. At the same time, the spatial parameter of step length was increased.

5.4.2.2 Backward walking: joint kinematics

In this section, the lower limb joint angles for the hip, knee, and ankle joint during BW were analysed. Figure 5.23 presents the variation in the joint angles, regulated by speeds and inclinations, for the respective 100% gait cycle, while Table 5.8 shows the statistical comparison.

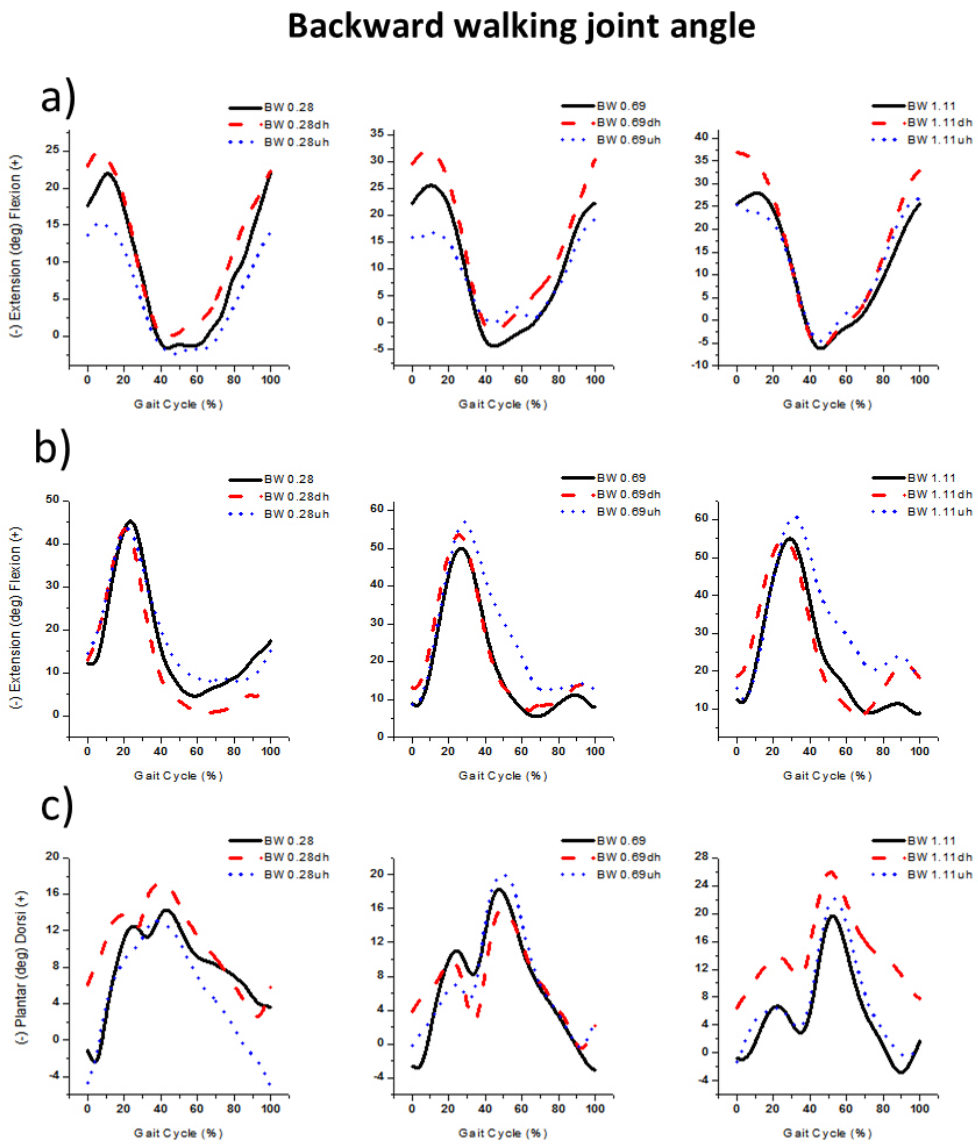


Figure 5.23 Comparison of the angle patterns of the a) hip, b) knee, and c) ankle joints during the BW gait cycle atthe three levels of inclination with respect to speed.
Solid black line: (0%), dh: downhill red dashed line (-5%) , uh: uphill blue dotted line (+5%)

The hip joint angle showed a similar pattern in respect of all the levels of inclination and speeds (Figure 5.23a). The total RoM also increased for all levels of inclination with an increase in speed.

A high level of knee joint flexion was seen in the stance phase at all levels of inclination and speeds (Figure 5.23b). The duration of the flexion was longer with an increase in speed. The RoM also increased with an increase in speed.

The ankle angle patterns were similar with two phases of dorsiflexion activity for the levels of inclination at the specific speed (Figure 5.23c). More dorsiflexion range was observed at the speed of 1.11m/s. The three respective levels of inclination showed little effect on the ankle angle at speed of 0.28m/s and 0.69m/s. Whereas at 1.11m/s a distinct enhancement was observed for BW on an inclined surface than was the case with BW on a level surface.

Statistical comparison of joint angle for the respective inclinations at varying speed during backward walking

Table 5.8 presents comparison for joint angle changes for BW on a level surface (0%) *versus* downhill walking (-5%); on a level surface (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%) at varying speed. The one-way ANOVA p-value was used to calculate the significance of the difference between joint angles at all inclinations at each speed. In this study, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycles. The correlation coefficient (r-value) was calculated to establish the relationship between joint angle change and the three inclinations at each of the three speeds.

Table 5.8 Comparison of joint angles during backward walking for the respective inclinations at each speed.

Joint angle (degree)	BW Speed (m/s)	0% / -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Hip	0.28	0.98	<0.001	0.99	<0.001	0.98	<0.001
	0.69	0.99	<0.001	0.98	<0.05	0.97	0.08
	1.11	0.98	<0.001	0.97	0.23	0.98	<0.001
Knee	0.28	0.95	<0.001	0.96	0.07	0.97	<0.001
	0.69	0.98	<0.001	0.94	<0.001	0.88	0.86
	1.11	0.91	<0.001	0.93	<0.001	0.73	<0.001
Ankle	0.28	0.72	<0.001	0.88	<0.001	0.94	<0.001
	0.69	0.86	0.80	0.93	<0.001	0.90	<0.001
	1.11	0.93	<0.001	0.98	<0.001	0.95	<0.001

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

The hip, knee and ankle angles show strong correlation ($r > 0.5$) for all of the inclinations. These statistical values are in line with the observed patterns shown in Figure 5.23. The p-value shows the significant difference for the joint angles at all of the inclinations and speeds. Exceptions were the non-significant difference in the hip angle for downhill as opposed to uphill walking at a speed of 0.69m/s; the knee angle for level as opposed to uphill walking at a speed of 0.28m/s and for uphill as opposed to downhill walking at a speed of 0.69m/s; and the ankle angle for level as opposed to downhill walking at 0.69m/s. Overall, the comparison for the joint angles at the respective inclinations revealed that the mean joint angle value in a gait cycle are significantly different ($p < 0.05$ and $p < 0.001$) though their patterns are linearly associated ($r > 0.50$).

5.4.2.3 Backward walking: joint kinetics

Joint moment

In this section, the lower limb joint moment for the hip, knee, and ankle joints were analysed for BW. Figure 5.24 presents the joint moment, regulated by speed and inclination, in each of the 100% gait cycle, while Table 5.9 shows the statistical comparison.

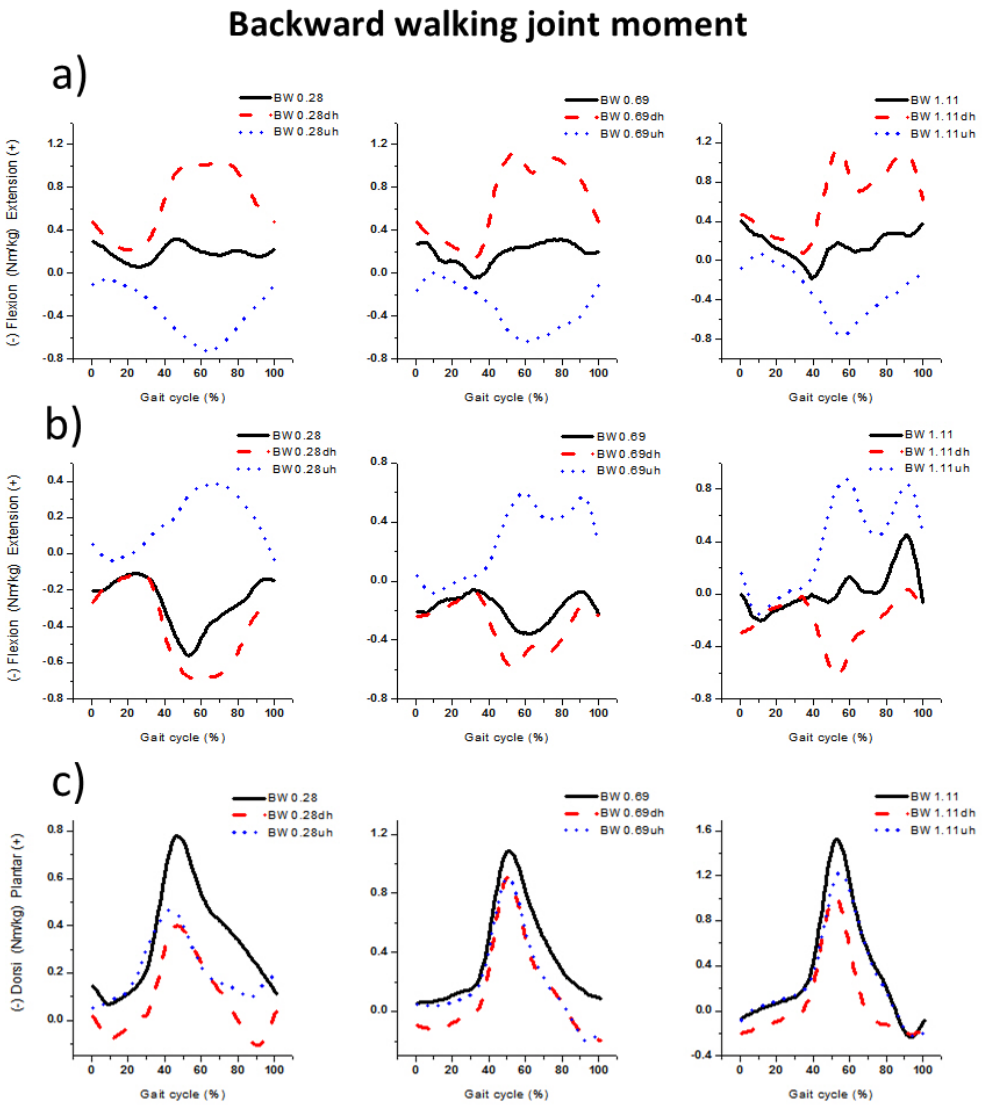


Figure 5.24 Comparison of the moment patterns for the a) hip, b) knee, and c) ankle joints during the BW gait cycle for the three levels of inclination with respect to speed.

Solid black line: (0%), dh: downhill red dashed line (-5%) , uh: uphill blue dotted line (+5%)

The hip joint moment (Figure 5.24a) at all speeds in uphill walking showed a flexor moment. In contrast, both downhill and level walking showed extensor moment.

The knee joint moment (Figure 5.24b) at all speeds in uphill walking showed an extensor moment; whereas level and downhill walking showed flexor moment. These flexor/extensor moment dependent on the level of inclination, were opposite in nature to those of the hip joint moment. It was found that the magnitude of the moment increases significantly in the case of inclined surfaces.

The ankle joint moment (Figure 5.24c) showed a similar pattern for all of the compared inclinations. Downhill walking showed a higher dorsiflexor moment during the heel-strike to

loading-response phase. A plantar flexor moment was observed in the loading-response to swing phase in all BW.

Statistical comparison of joint moment at the respective levels of inclination at varying speed during backward walking

Table 5.9 presents comparison for joint moment for BW on a level surface (0%) *versus* downhill walking (-5%); backward level walking (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%) at varying speed. The one- way ANOVA p-value was used to calculate the significance of the difference between the joint moment at all of the inclinations at each speed. In this study, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycles. The correlation coefficient (r-value) was calculated to establish the relationship between joint moment and the levels of inclinations at each speed.

Table 5.9 Comparison of joint moment during backward walking for the respective inclinations at each speed.

Joint moment (Nm/kg)	BW Speed (m/s)	0% / -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Hip	0.28	-0.54	<0.001	0.74	<0.001	-0.93	<0.001
	0.69	0.72	<0.001	-0.49	<0.001	-0.90	0.08
	1.11	0.63	<0.001	0.04	<0.001	-0.64	<0.001
Knee	0.28	-0.61	<0.001	0.79	<0.001	-0.91	<0.001
	0.69	0.80	<0.001	-0.44	<0.001	-0.65	<0.001
	1.11	0.80	<0.05	0.17	<0.001	-0.32	<0.001
Ankle	0.28	0.93	<0.001	0.77	<0.001	0.83	<0.001
	0.69	0.98	<0.001	0.94	0.10	0.97	<0.001
	1.11	0.95	<0.001	0.99	0.67	0.91	<0.001

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

The hip and knee joint moment showed negative correlation for uphill and downhill walking at all speeds. Ankle joint moment showed positive correlation at all three of the inclinations and speeds. These statistical value are in line with the observed patterns, as shown in Figure 5.24. The p-value shows the significant difference in joint moment at all of the compared inclinations and speeds except for the comparison between level and uphill walking for the ankle joint at speed of 0.69m/s and 1.11m/s.

Joint power

In this section, the lower limb joint power for the hip, knee, and ankle joints was analysed for BW. Figure 5.25 presents the joint power, regulated by speed and inclination, for each of the 100% gait cycle, while Table 5.10 shows the statistical comparison.

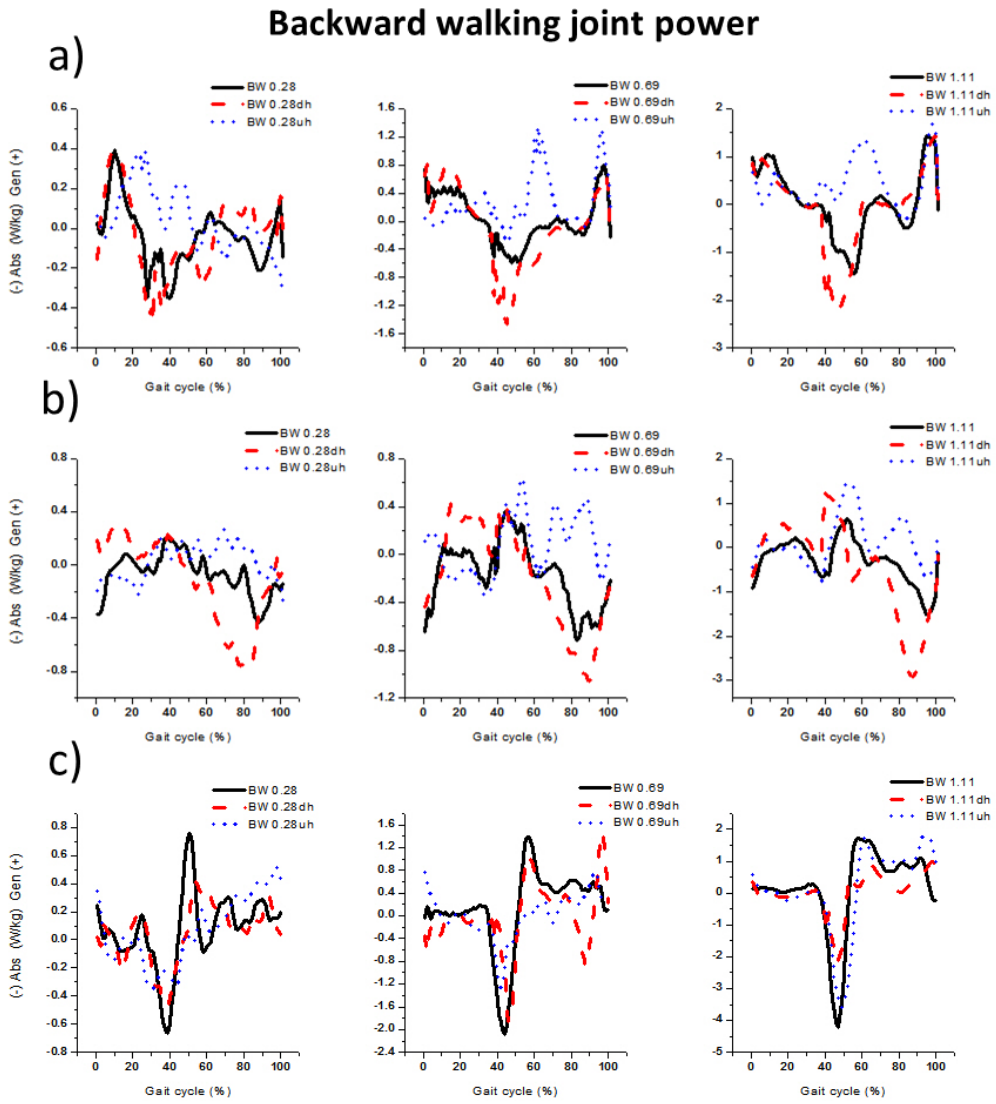


Figure 5.25 Comparison of the power patterns of the a) hip, b) knee, and c) ankle joints during the BW gait cycle for the three levels of inclination with respect to speed.
Solid black line: (0%), dh: downhill red dashed line (-5%), uh: uphill blue dotted line (+5%)

This study showed that the hip and knee joints are able to absorb and generate power at all speeds in level and downhill walking. Uphill walking involved a greater generation of power than was the case with level and downhill walking. It was found that in both types of walking, a greater magnitude of power could be produced by the hip and knee joints by increasing the speed (Figures 5.25a and b).

The power patterns associated with the ankle joint were found to be similar for the respective levels of inclination and speeds. The ankle joint showed significant levels of power absorption from the toe-off to the pre-swing phase at all inclinations and speeds. It was found that in both types of walking, greater magnitudes of power are generated by the ankle joint by increasing the speed (Figure 5.25c).

Statistical comparison of joint power at the respective inclinations at varying speed during backward walking

Table 5.10 presents comparison for joint power for BW on a level surface (0%) *versus* downhill walking (-5%); level walking (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%) at varying speed. The one-way ANOVA p-value was used to calculate the significant difference between joint power at all inclinations at each speed. In this study, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycles. The correlation coefficient (r-value) was calculated to establish the relationship between joint power at the respective inclinations at each speed.

Table 5.10 Comparison of joint power in backward walking for the respective inclinations at each speed.

Joint power (W/kg)	BW Speed (m/s)	0% / -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Hip	0.28	0.54	0.36	0.26	<0.001	-0.49	<0.05
	0.69	0.79	0.95	0.01	<0.001	-0.42	<0.001
	1.11	0.62	0.45	0.62	<0.001	0.02	<0.001
Knee	0.28	0.71	0.83	-0.06	<0.05	-0.25	<0.001
	0.69	0.89	0.28	0.27	0.95	0.11	0.43
	1.11	0.82	0.44	0.14	<0.001	0.15	<0.001
Ankle	0.28	0.69	0.88	0.49	0.92	0.57	0.93
	0.69	0.66	0.18	0.73	0.17	0.35	0.99
	1.11	0.88	0.76	0.80	0.99	0.79	0.81

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

For joint power in the case of the hip and knee, the first comparison for walking on a level surface as opposed to downhill walking shows a strong correlation, while the p-value show non-significant difference. The second and third comparison for level walking as opposed to uphill walking, and uphill as opposed to downhill walking show weak correlation with the p-value

pointing to a significant difference. For ankle joint power, all of the compared inclination levels showed strong correlation, while the p-value showed a non-significant difference. These statistical values are in line with the observed patterns, as shown in Figure 5.25.

Muscle activity

Among the 92 simulated muscles in the anthrometric model, seven keymuscles were chosen for studying the hip, knee and ankle joints. The activity levels of three hip joint muscles (the GM, the Gmed, and the IL), of two biarticular muscles used in both the hip and the knee joint (the RF and the BF), and of two ankle joint muscles (the TA and the LGAS) were plotted for analysis. Figures 5.26 to 5.28 present the muscle activity levels, which are regulated by speed and inclination, while Table 5.11 shows the statistical comparison.

Hip joint muscles: Figure 5.26 shows comparison of the activity levels of the GM, Gmed and IL muscles during BW for the three levels of inclination with respect to speed .

The activity levels of the GM muscle (Figure 5.26a) are similar in the case of level and uphill walking at all speeds. During level and uphill walking, the activity levels of the GM muscle increase gradually from the toe-strike to the swing phase of the gait cycle. Downhill walking brings about greater muscle activity in the entire gait cycle.

The activity patterns of the Gmed muscle (Figure 5.26b) are similar in the case of level and uphill walking at each speed. The magnitudes of muscle activity were found to vary according to the respective levels of inclination. During level and uphill walking, the Gmed muscle were found to be active in two phases, one in the toe-strike phase and the other in the mid-swing phase. Downhill walking show greater muscle activity during the entire gait cycle, specifically, in the loading-response phase when peak activity was observed.

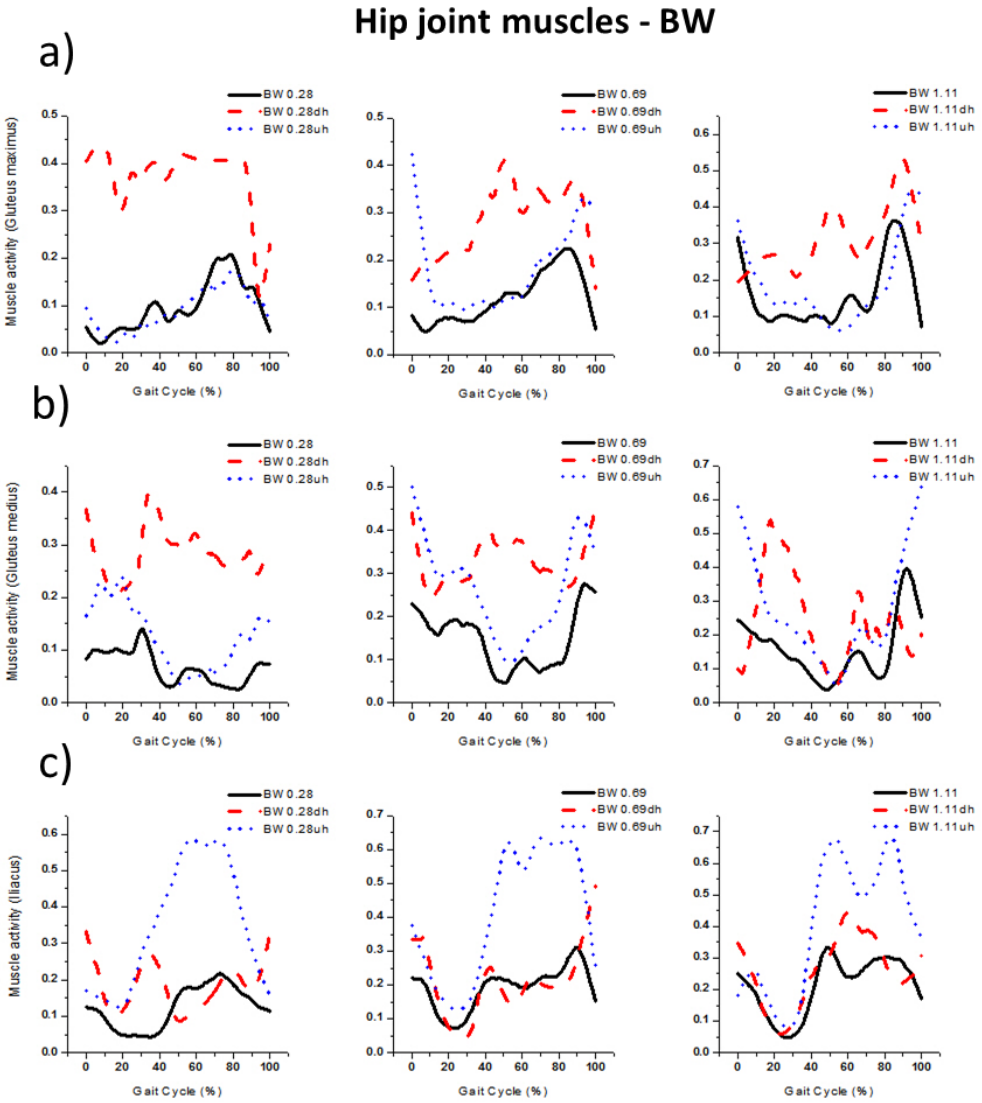


Figure 5.26 Comparison of the activity levels of the a) gluteus maximus, b) gluteus medius, and c) iliacus muscles during the BW gait cycle for the three levels of inclination with respect to speed.

Solid black line: (0%), dh: downhill red dashed line (-5%), uh: uphill blue dotted line (+5%)

The activity levels of the IL muscle (Figure 5.26c) were found to differ according to the level of inclination. The greater magnitude of muscle activity was observed in uphill walking. The IL muscle was found to be active from mid-stance to the terminal-swing phase for all levels of inclination and speed.

Biarticular muscles of the hip and knee joints: Figure 5.27 shows comparison of the activity of the RF and BF muscle during BW for the three levels of inclination with respect to speed

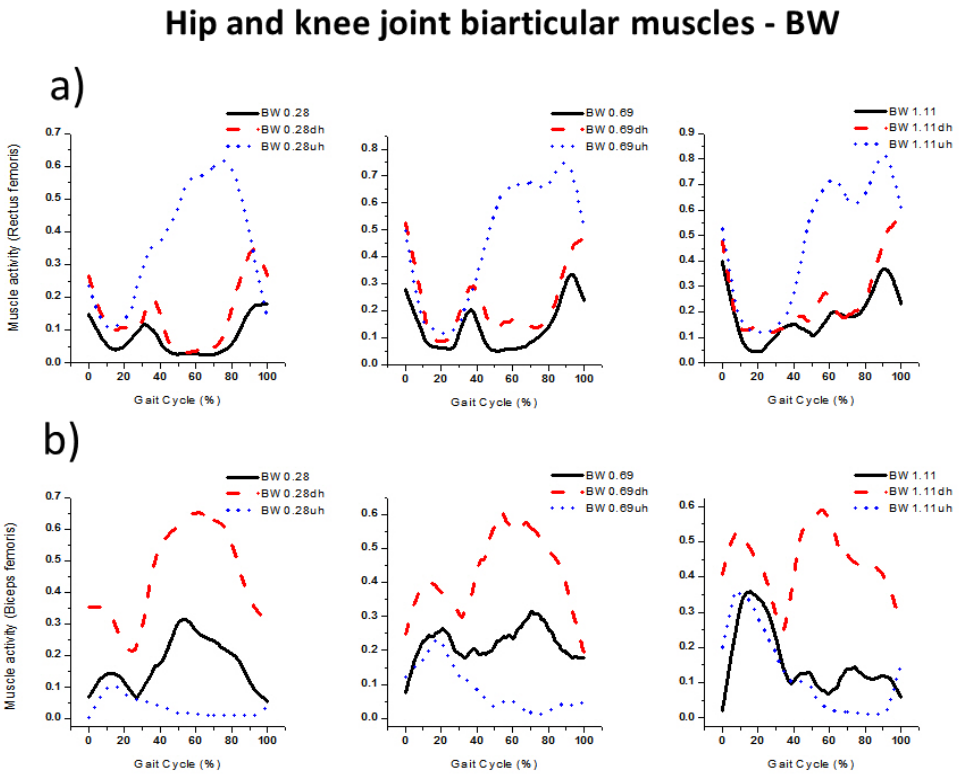


Figure 5.27 Comparison of the activity levels of the a) rectus femoris and b) biceps femoris muscles during the BW gait cycle for the three levels of inclination with respect to speed.
Solid black line: (0%), dh: downhill red dashed line (-5%) , uh: uphill blue dotted line (+5%)

The activity levels for the RF muscle (Figure 5.27a) were found to be similar for all speeds. A greater magnitude of muscle activity was observed in uphill walking. The RF muscles were active in two phases: the one in the toe-strike phase and the other in the mid-stance to terminal-swing phase for all levels of inclination and speed.

The activity patterns for the BF muscle (Figure 5.27b) were found to be similar at all speeds. In contrast to the RF muscles, a higher magnitude of muscle activity was observed in downhill walking. The BF muscles also revealed activity in two phases: one in the toe-strike phase and the other in the mid-stance to terminal-swing phase which were applicable at all speeds, the only exception being on an uphill incline.

Ankle joint muscles: Figure 5.28 shows the activity levels of the TA and LGas muscles during BW for the three levels of inclination with respect to speed

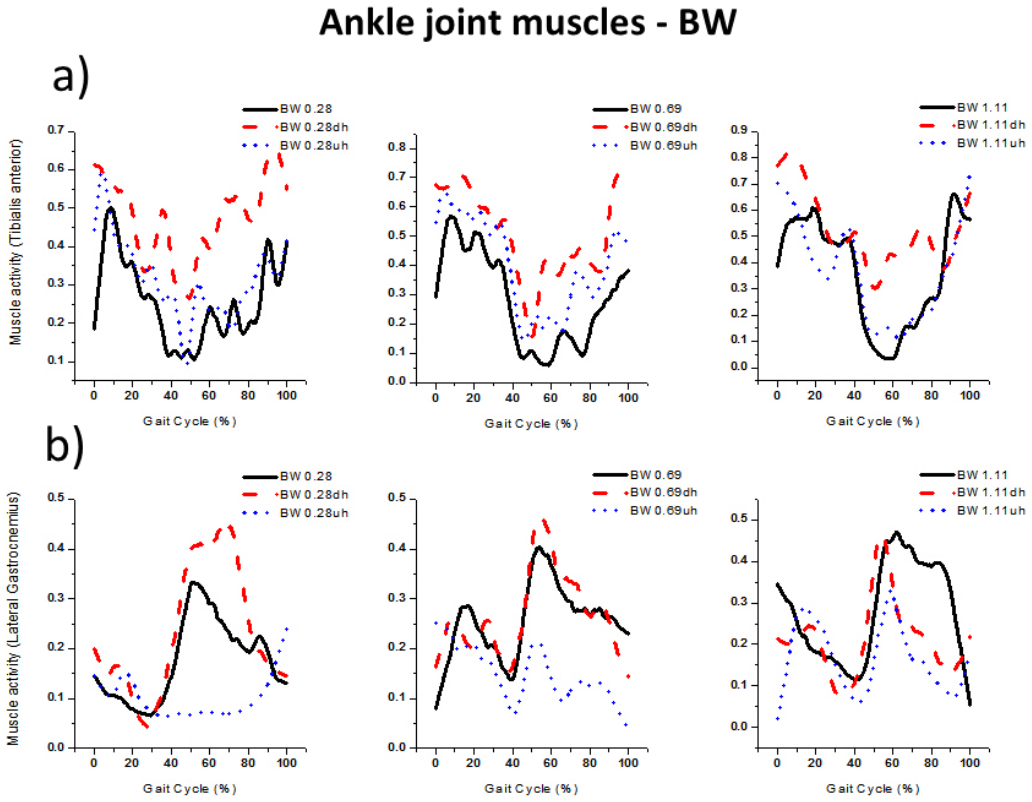


Figure 5.28 Comparison of the activity levels of the a) tibialis anterior and b) lateral gastrocnemius muscles during the BW gait cycle for the three levels of inclination with respect to speed.

Solid black line: (0%), dh: downhill red dashed line (-5%), uh: uphill blue dotted line (+5%)

The activity levels for the TA muscle (Figure 5.28a) were found to be similar at all speeds. These muscles were largely involved in two peak activities, one in the loading-response phase and the other in the pre-swing phase at all levels of inclination and speed.

The activity patterns for the LGas muscle (Figure 5.28b) were found to vary according to the level of inclination and speed. The lowest magnitude of muscle activity was observed in uphill walking. More intensive activity in the LGas muscle was found during the mid-stance to terminal-swing phase of the gait cycle and at all levels of inclination.

Statistical comparison of muscle activity for the three levels of inclination at varying speed during backward walking

Table 5.11 presents comparison for muscle activity for BW on a level surface (0%) *versus* downhill walking (-5%); BW on a level surface (0%) *versus* uphill walking (5%); and downhill walking (-5%) *versus* uphill walking (5%) at varying speed. The one-way ANOVA p-value was used to calculate the significant difference between muscle activities at all inclinations at each speed. In this study, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycles. The correlation coefficient (r-value) was calculated to establish the relationship between muscle activity and the respective inclinations at each speed.

Table 5.11 Comparison of muscle activity during backward walking for the respective inclinations at each speed.

Muscle activity	BW Speed (m/s)	0% / -5% Inclination		0% / 5% Inclination		-5% / 5% Inclination	
		r	p	r	p	r	p
Gluteus maximus	0.28	0.07	<0.001	0.88	0.46	0.08	<0.001
	0.69	0.71	<0.001	0.41	<0.001	-0.05	<0.001
	1.11	0.62	<0.001	0.59	<0.001	0.37	<0.001
Gluteus medius	0.28	-0.06	<0.001	0.73	<0.001	-0.41	<0.001
	0.69	-0.05	<0.001	0.89	<0.001	-0.25	<0.001
	1.11	0.08	<0.001	0.87	<0.001	0.01	<0.05
Iliacus	0.28	0.16	<0.001	0.74	<0.001	-0.27	<0.001
	0.69	0.62	<0.05	0.81	<0.001	0.28	<0.001
	1.11	0.78	<0.001	0.91	<0.001	0.74	<0.001
Biceps femoris	0.28	0.91	<0.001	-047	<0.001	0.68	<0.001
	0.69	0.65	<0.001	-0.20	<0.001	-0.53	<0.001
	1.11	-0.02	<0.001	0.79	<0.001	-0.03	<0.001
Rectus femoris	0.28	0.93	<0.001	-0.41	<0.001	-0.31	0.54
	0.69	0.91	<0.001	0.25	<0.001	0.22	<0.001
	1.11	0.87	<0.001	0.71	<0.001	0.65	<0.001
Tibialis anterior	0.28	0.67	<0.001	0.77	<0.001	0.62	<0.001
	0.69	0.83	<0.001	0.93	<0.001	0.89	<0.001
	1.11	0.63	<0.001	0.85	0.98	0.76	<0.001
Lateral Gastrocnemius	0.28	0.90	<0.001	-0.41	<0.001	-0.45	<0.001
	0.69	0.85	<0.001	0.02	<0.001	0.19	0.09
	1.11	0.50	<0.001	0.27	<0.001	0.57	<0.001

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

The intensity of muscle activity significantly depends on the nature of burst. The statistical comparison of muscle activities for the respective levels of inclination show significant differences ($p < 0.05$ and $p < 0.001$) with the range of the correlation coefficient being $r = -0.53$

to 0.93. The muscles were found to be active in both concentric and eccentric contraction during the flexion and extension movements. During this activity, the shape, magnitude and duration of burst were significantly different, as reflected in the p-value.

5.4.3 Comparison between FW and BW in terms of kinematics and kinetics at the three levels of inclination and speed

5.4.3.1 Comparison between FW and BW: temporal and spatial gait parameters

Figure 5.29 (a) and (b) shows the temporal and spatial parameters such as gait cycle time, step time, double limb support (DLS), and step length during FW and BW.

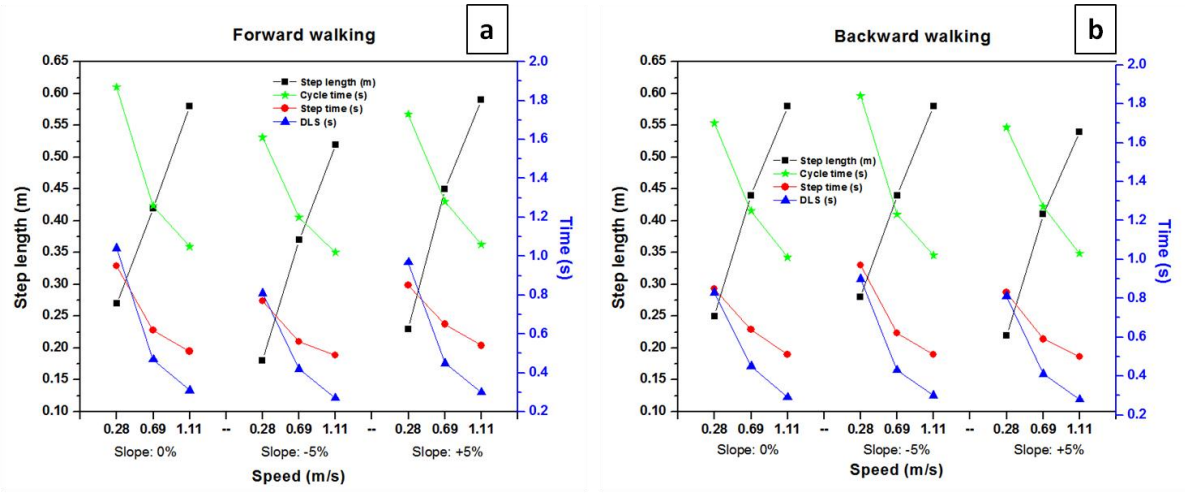


Figure 5.29 Temporal and spatial parameters for step length, gait cycle time, step time, and double leg support at three levels of inclination and speed.

(a) Represents FW and (b) represents BW: the black line indicates step length; the green line indicates cycle time; the red line indicates step time; and the blue line indicates double limb support.

The temporal parameters such as gait cycle time, step time and DLS declined with an increase in speed for all of the levels of inclination in both FW and BW. Similarly, the spatial parameter of step length was increased.

5.4.3.2 Comparison between FW and BW: joint kinematics

In this section, the lower limb joint angle for each of the hip, knee, and ankle joints was analysed for FW and BW. Figures 5.30 to 5.32 present the joint angles, regulated by speed and inclination, in each of the 100% gait cycle, while Table 5.12 shows the statistical comparison.

Hip joint angle: Figure 5.30 shows comparison for the hip joint angle for FW and BW at all levels of inclination and at each speed

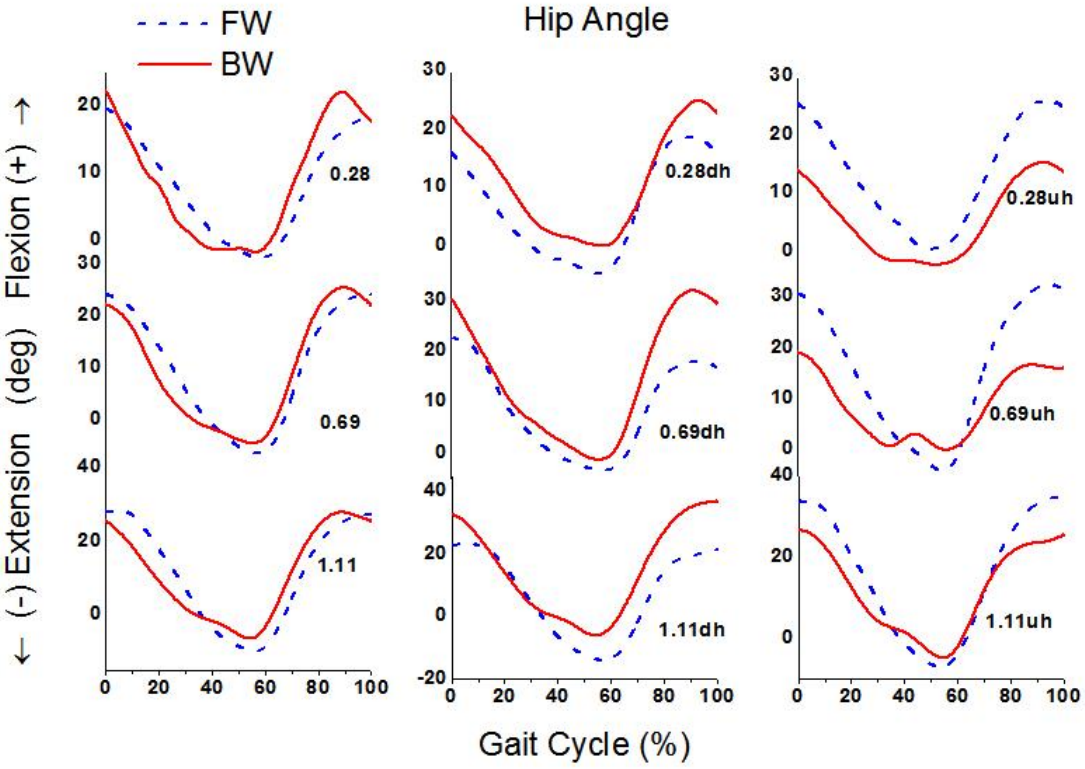


Figure 5.30 Hip joint angle during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The hip joint angle for both FW and time-reversed BW oscillated from a flexion of 0% to a flexion of 100%. In this study, the transition patterns of the angles were smoother in FW than in BW.

Knee joint angle: Figure 5.31 shows comparison of the knee joint angle for FW and time-reversed BW for the respective levels of inclination for each speed

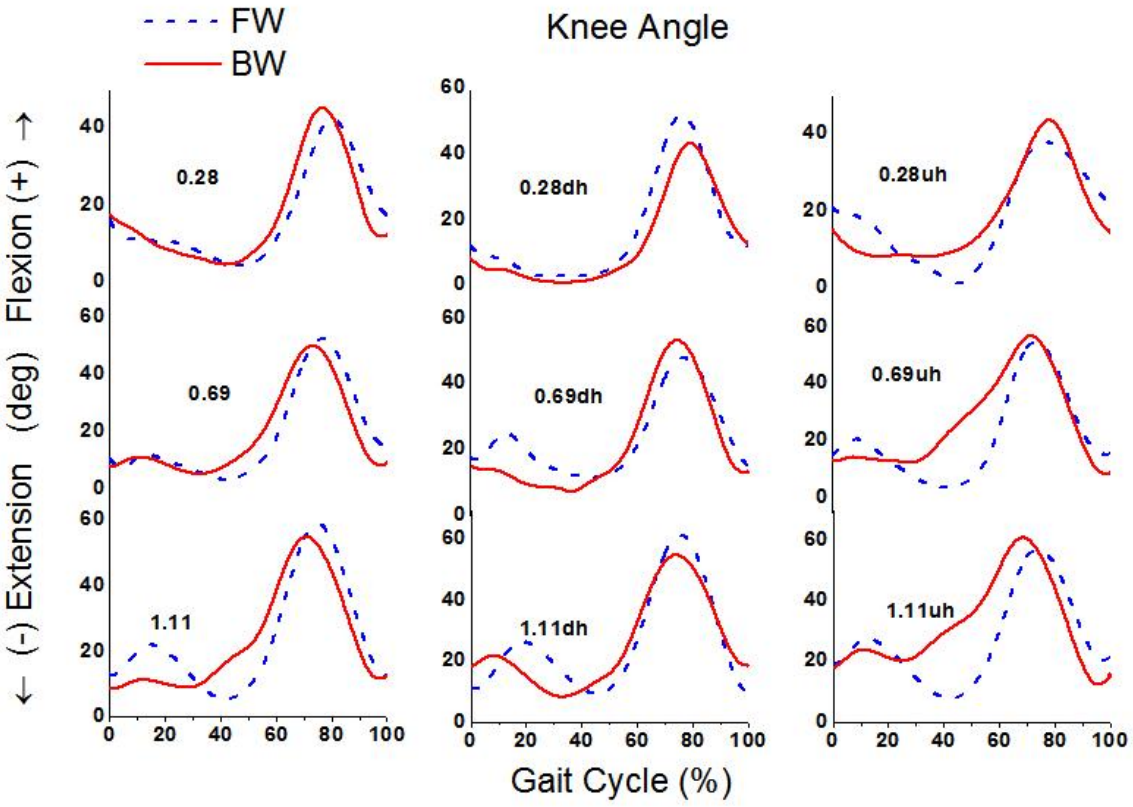


Figure 5.31 Knee joint angle during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; redline: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

Both FW and time-reversed BW revealed two flexion in most type of walking. In this study, the knee assumed a neutral position between flexion in FW, thus bringing two distinct peaks into the pattern. In BW, the transition between the flexion was found to be shallow. This shows the occurrence of smaller knee movements in BW than in FW.

Ankle joint angle: Figure 5.32 shows comparison of the ankle joint angle for FW and BW at all three of the inclinations and at each speed

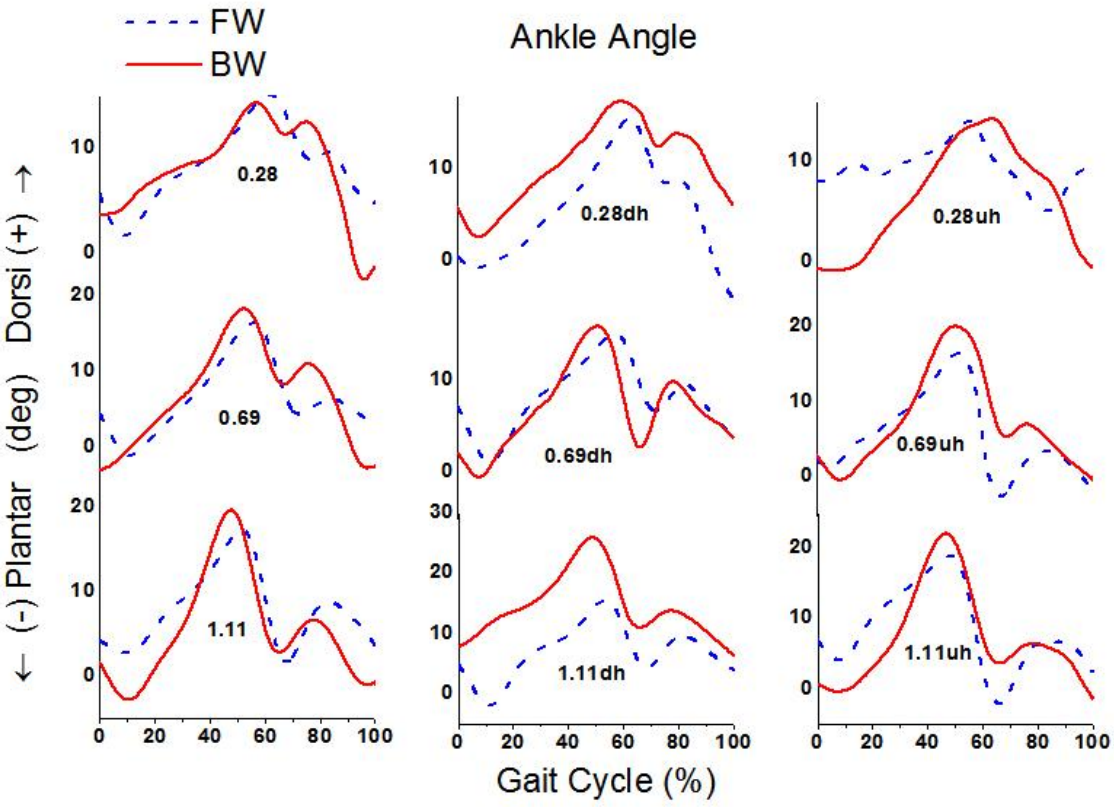


Figure 5.32 Ankle joint angle during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; redline: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The ankle joint angle shows similar patterns for both FW and time-reversed BW. In this study, two plantar flexor movements in the ankle joint were observed in one gait cycle.

Statistical comparison of joint angles for forward and backward walking at varying speed and at all levels of inclination

Table 5.12 presents the ankle joint angle during FW/BW at the three respective inclinations and speed. The one-way ANOVA p-value was used to calculate the significant difference between the joint angles for all inclinations at each speed. Here, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycles. The correlation coefficient (r-value) was calculated to establish the relationship between the joint angles and the three respective inclinations at each speed.

Table 5.12 Comparison of joint angles between FW and BW for three levels of inclination and speed.

Joint angle (deg)	FW/BW Inclination	FW/BW speed					
		0.28 (m/s)		0.69 (m/s)		1.11 (m/s)	
		r	p	r	p	r	p
Hip	0%	0.91	0.12	0.94	0.66	0.91	0.95
	-5%	0.97	<0.001	0.94	<0.001	0.91	<0.001
	+5%	0.98	<0.001	0.96	<0.001	0.98	<0.001
Knee	0%	0.92	0.38	0.91	0.64	0.86	0.29
	-5%	0.95	<0.001	0.93	<0.001	0.91	0.25
	+5%	0.88	0.38	0.78	<0.001	0.65	<0.001
Ankle	0%	0.77	0.14	0.85	<0.05	0.89	<0.001
	-5%	0.97	<0.001	0.82	<0.001	0.74	<0.001
	+5%	0.35	<0.001	0.81	<0.001	0.80	<0.001

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

The hip, knee and ankle angles showed strong correlation ($r > 0.50$) for FW/BW at all speeds and inclinations. These statistical value are in line with the observed patterns, shown in Figures 5.50 to 5.52. Most of the p-value proved to be statistically significant. The only exceptions were the hip angle during level walking (0%) at all three speeds; the knee angle during level walking (0%) and downhill walking (-5%) at a speed of 1.11m/s and uphill walking (+5%) at a speed of 0.28m/s and the ankle angle during level walking (0%) at a speed of 0.28m/s. Overall, the mean angle value for FW and BW were significantly different ($p < 0.05$ and $p < 0.001$) though their patterns in each gait cycle showed a linear association ($r > 0.50$).

5.4.3.3 Comparison of FW and BW: joint kinetics

Joint moment

In this section, an analysis of lower limb joint moment for the hip, knee, and ankle joints was carried out for FW and BW respectively. Figures 5.33 to 5.35 present the joint moment, which are regulated by speed and inclination, in each of the 100% gait cycle, while Table 5.13 shows the statistical comparison.

Hip joint moment: Figure 5.33 shows comparison of the hip joint moment for FW and BW respectively at all inclinations and at each speed.

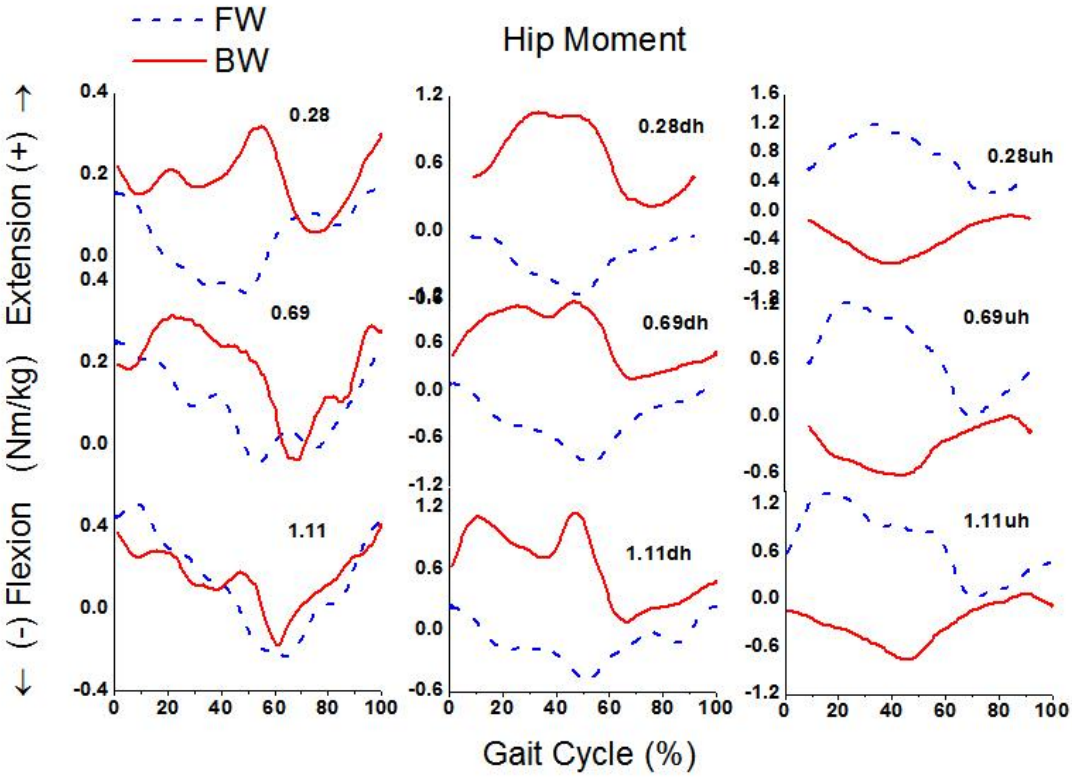


Figure 5.33 Hip joint moment during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; redline: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s

The hip joint moment in forward and backward walking on a level surface involves mostly extensor moment in each gait cycle. Forward walking on a downhill inclination and BW on an uphill inclination involves flexor moment as opposed to the extensor moment in FW on an uphill inclination and BW on a downhill inclination. In essence, forward and backward walking involve opposite moment patterns when there is some degree of inclination.

Knee joint moment: Figure 5.34 shows comparison for the knee joint moment for FW and BW respectively for all three of the inclinations and at each of the speed

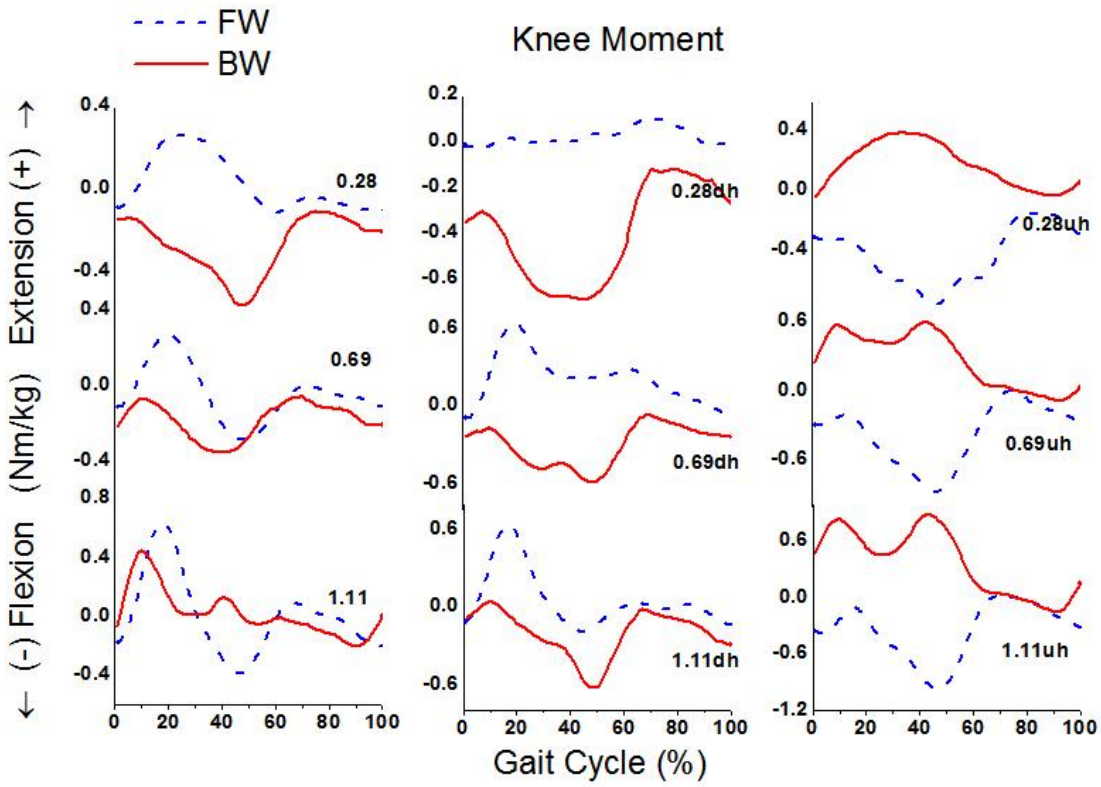


Figure 5.34 Knee joint moment during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW: dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

It was found that the knee joint moment in forward and backward walking on a level surface involved both flexor and extensor moment in a gait cycle, except when a speed of 0.28m/s was maintained. Forward walking on a downhill inclination and BW on an uphill inclination involved extensor moment. This was in contrast to the flexor moment associated with FW on an uphill and BW on a downhill inclination. In essence, forward and backward walking involve opposite moment patterns when there is some degree of inclination.

Ankle joint moment: Figure 5.35 shows comparison for ankle joint moment for FW and BW for all three of the levels of inclination and at each speed.

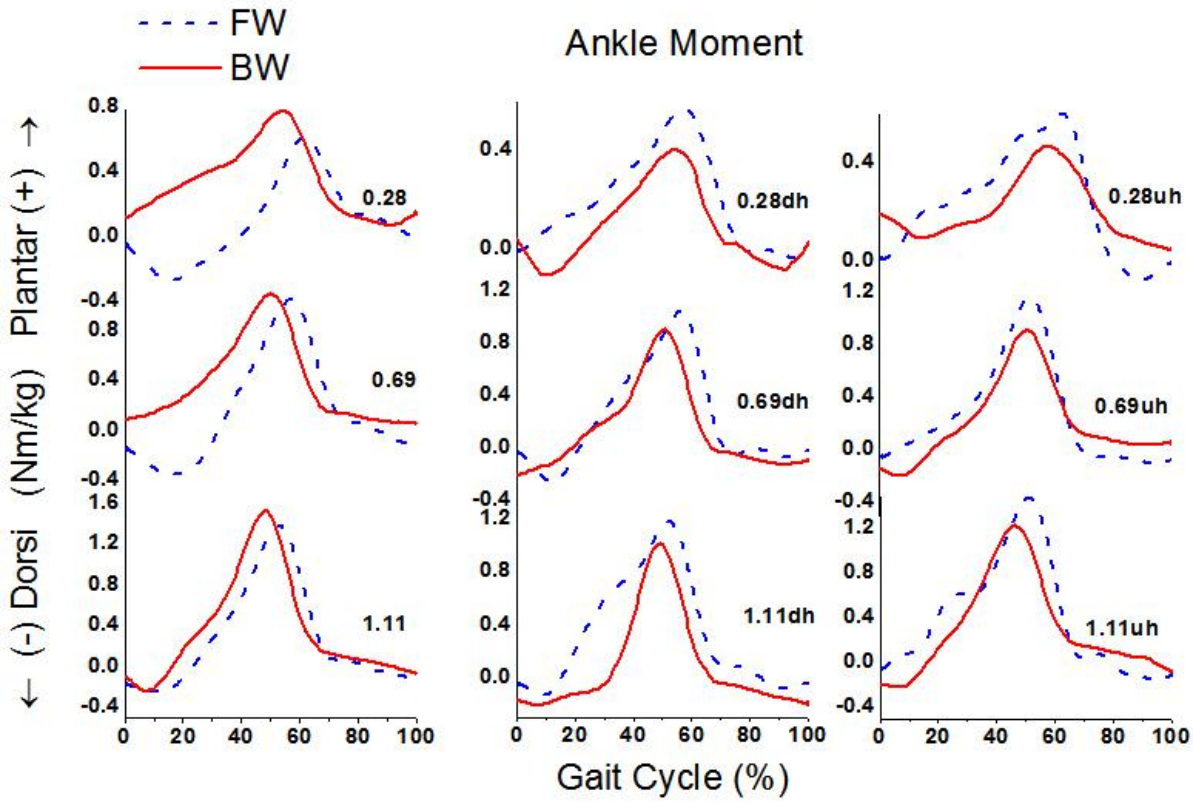


Figure 5.35 Ankle joint moment during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The ankle joint moment in BW on a level surface involved more plantar flexor moment than in FW at all speeds. On the other hand, though, FW on an inclined surface involved more plantar flexor moment than in the case of BW. During both forward and backward walking on inclined surfaces, similar patterns of plantar flexor moment were observed at all speeds.

Statistical comparison of joint moment patterns for forward and backward walking at varying speed and at all inclination

Table 5.13 presents the joint moment during FW/BW at the three respective inclinations and speeds. A one-way ANOVA p-value was used to calculate the significant difference between the joint moment at all three of the respective inclinations and speeds. In this study, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycle. The correlation

coefficient (r-value) was calculated to establish the relationship between the joint moment and the respective inclinations and speeds.

Table 5.13 Comparison of joint moment between FW and BW for three levels of inclination and speed.

Joint moment (Nm/kg)	FW/BW Inclination	FW/BW speed					
		0.28 (m/s)		0.69 (m/s)		1.11 (m/s)	
		r	p	r	p	r	p
Hip	0%	-0.51	<0.001	0.53	<0.001	0.84	<0.05
	-5%	0.91	<0.001	-0.59	<0.001	-0.27	<0.001
	+5%	0.94	0.07	-0.83	<0.001	-0.57	<0.001
Knee	0%	-0.11	<0.001	0.46	<0.001	0.57	<0.001
	-5%	-0.17	<0.001	-0.71	<0.001	0.55	<0.001
	+5%	0.91	0.26	-0.32	<0.001	-0.68	<0.001
Ankle	0%	0.46	<0.001	0.76	0.23	0.94	0.23
	-5%	0.93	<0.001	0.93	0.09	0.90	<0.001
	+5%	0.86	0.23	0.93	0.23	0.91	0.15

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

The comparison between FW and time-reversed BW show that hip and knee joint moment showed mostly negative correlation with statistically significant difference. In contrast, the ankle joint moment showed positive correlation for all levels of inclination and speed.

Joint power

In this section, lower limb joint power for the hip, knee, and ankle joints was analysed for FW and BW. Figures 5.36 to 5.38 show the joint power, regulated by speed and inclination, for each of the 100% gait cycle, while Table 5.14 shows the statistical comparison.

Hip joint power: Figure 5.36 shows the hip joint power comparison between FW and BW at all three of the inclinations and at each of the speed.

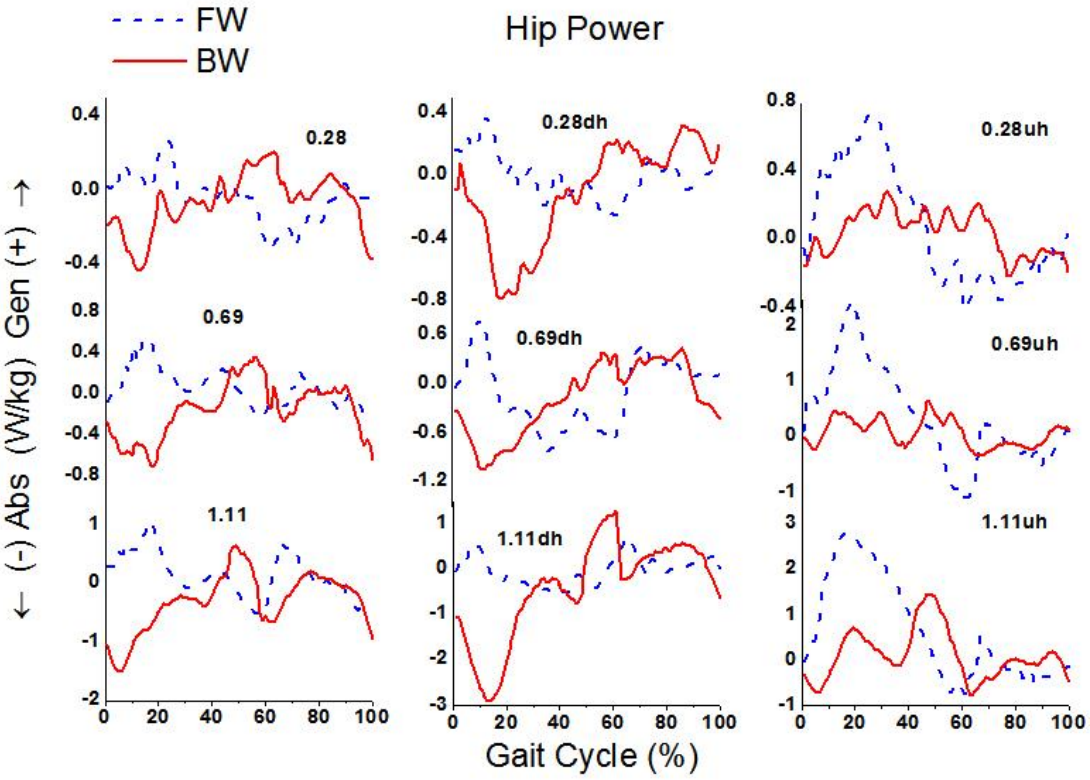


Figure 5.36 Hip joint power during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The hip joint was found to generate and absorb power on a level surface in both forward and backward walking. On an inclination, BW downhill involved more power absorption than was the case with FW. In contrast, FW uphill generated more power at all speeds than BW.

Knee joint power: Figure 5.37 shows comparison of knee joint power for FW and BW respectively at all three of the inclinations and at each speed.

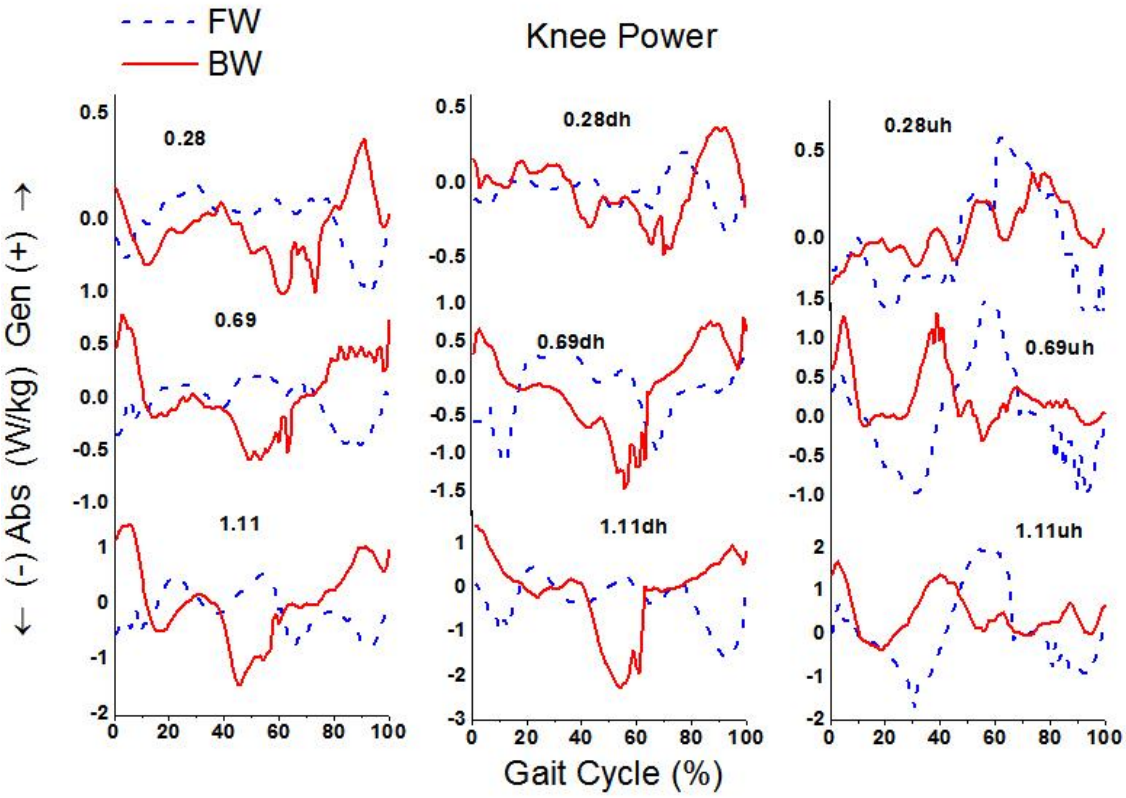


Figure 5.37 Knee joint power during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

As in the case of the hip joint, the knee joint involved both the generation and the absorption of power in forward and backward walking on a level surface. BW on a downhill inclination involved more power absorption by the knee joint than was the case with FW. It was on the uphill inclination, however, and in FW that the knee joint generated and absorbed more power. On the other hand BW involved the generation of more power by the knee joint on the uphill inclination at all three of the speeds.

Ankle joint power: Figure 5.38 shows comparison of the ankle joint power for FW and BW respectively for all three levels of inclination and at each speed.

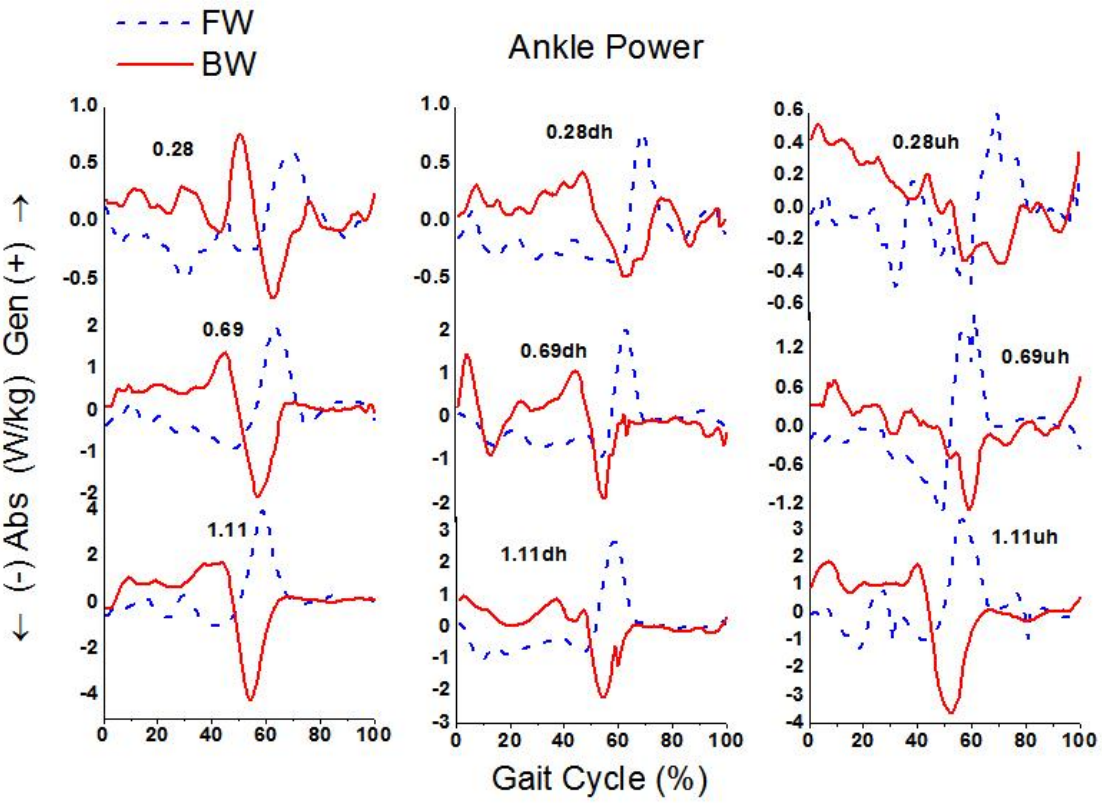


Figure 5.38 Ankle joint power during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

For all three of the inclinations and speed, the ankle joint showed maximum power absorption during the loading-response phase of BW, as well as maximum power generation during the pre-swing phase of FW.

Statistical comparison of joint power patterns for forward and backward walking at varying speed and at all three of the levels of inclination

Table 5.14 presents the joint power during FW/BW at the three levels of inclination and speed. The one-way ANOVA p-value was used to calculate the significance of the difference between joint power at all three of the respective inclinations and speeds. In this study, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycles. The correlation coefficient (r-value) was calculated to establish the relationship between joint power and the respective inclinations and speeds.

Table 5.14 Comparison of joint power between FW and BW for three levels of inclination and speed.

Joint power (W/kg)	FW/BW Inclination	FW/BW speed					
		0.28 (m/s)		0.69 (m/s)		1.11 (m/s)	
		r	p	r	p	r	p
Hip	0%	-0.53	0.22	-0.46	<0.001	-0.36	<0.001
	-5%	-0.37	<0.05	-0.15	0.19	-0.31	<0.001
	+5%	0.45	0.28	0.38	<0.001	-0.12	0.58
Knee	0%	-0.63	0.07	-0.77	0.08	-0.65	<0.05
	-5%	-0.35	0.51	-0.23	0.44	-0.49	<0.05
	+5%	0.57	<0.05	-0.04	<0.001	0.03	<0.001
Ankle	0%	-0.57	<0.001	-0.51	0.13	-0.71	0.65
	-5%	0.33	<0.001	0.02	0.22	-0.67	0.39
	+5%	-0.20	<0.05	-0.58	0.44	-0.54	0.76

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

At all the inclinations and speeds, most of the value for hip, knee, and ankle joint power showed a negative correlation for FW and time-reversed BW. This is because the power that is generated during a part of the gait cycle in FW is then absorbed in that same part of the cycle during BW. Some of the value for hip, knee, and ankle joint power showed a positive correlation with inclinations and speeds; in these instances, joint power was either absorbed or generated for both FW and BW at that same part of the gait cycle.

Mixed results were found for FW and time-reversed BW. There was no significant difference between FW and BW for the p-value of hip power at a speed of 0.28m/s in level walking; of knee power at 0.28m/s and 0.69m/s in level and downhill walking; and of ankle power at 0.69m/s and 1.11m/s for all inclinations. A significant difference was seen between FW and BW for the p-value of hip power at 0.28m/s on a downhill inclination, at 0.69m/s on the level and on the uphill inclination, at1.11m/s on the level and on the downhill inclination; of knee power at 1.11m/s for all inclinations and on uphill inclination at all speeds; and of ankle power at 0.28m/s for all inclinations.

Distribution of joint power in each joint

Power generation: Figure 5.39(a) and (b) shows the distribution of power generation by the lower limb joints (hip, knee, and ankle) in FW and BW at all of the studied inclinations (-5%, 0%, and +5%) and speeds (0.28 m/s, 0.69 m/s, and 1.11 m/s).

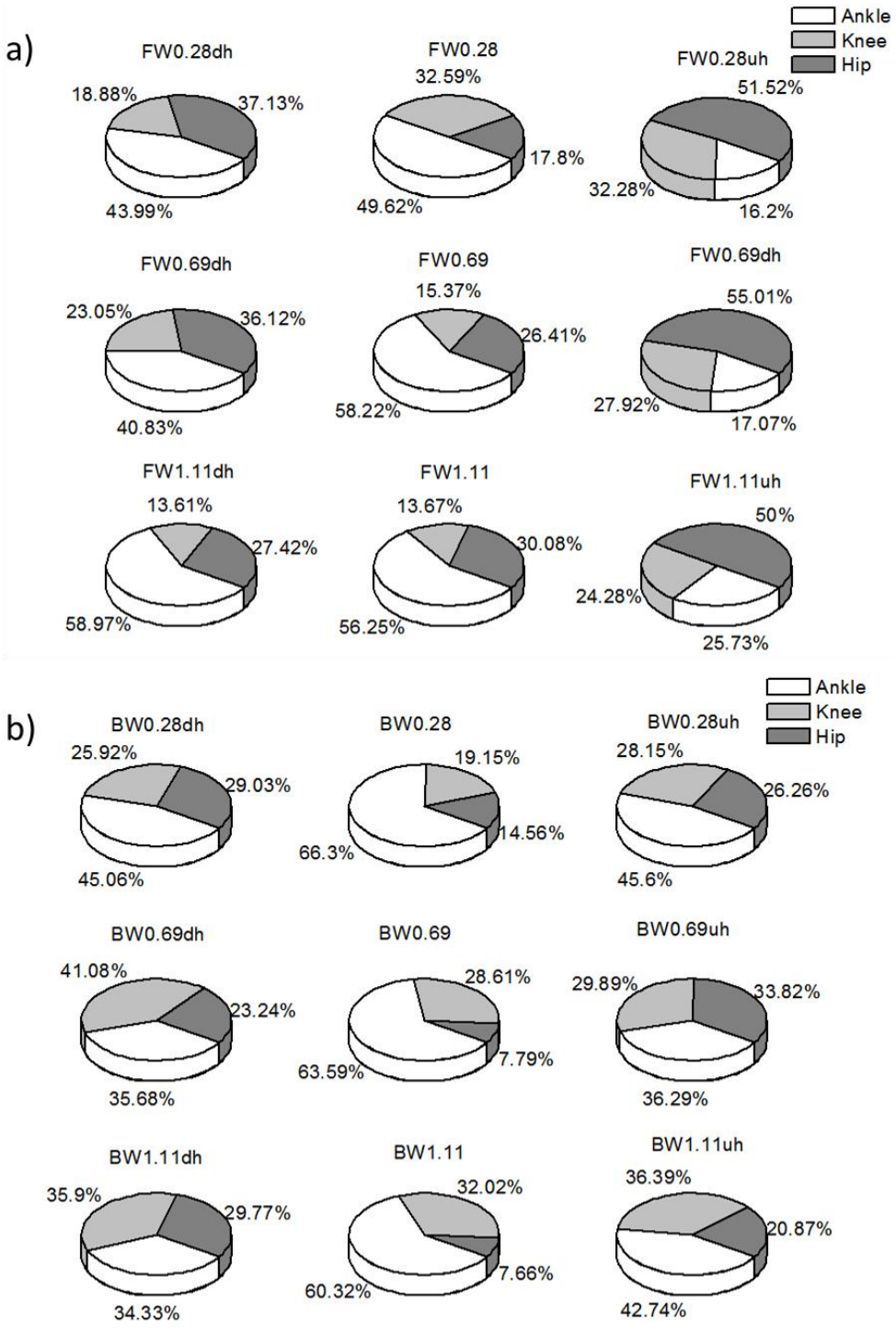


Figure 5.39 Distribution of power generation in each of the lower limb joints.

In this diagram, (a) represents FW; (b) represents BW; the white colour represents the ankle joint; the light grey colour represents the knee joint; and the dark grey colour represents the hip joint.

Power absorption: Figure 5.40 (a) and (b) shows the distribution of joint power generation by the lower limb joints (hip, knee, and ankle) during FW and BW at all of the studied inclinations (-5%, 0%, and +5%) and speeds (0.28 m/s, 0.69 m/s, and 1.11 m/s).

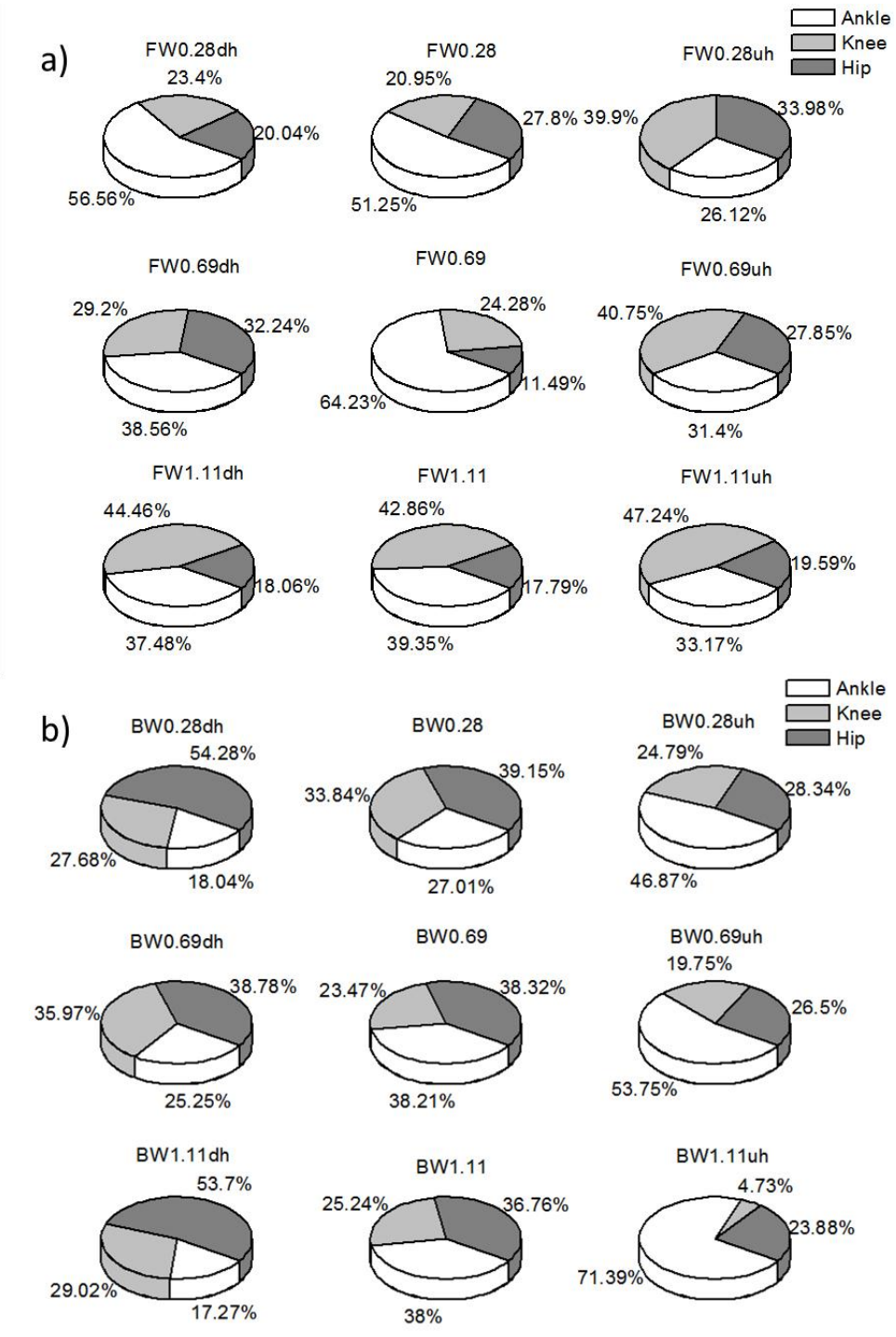


Figure 5.40 Distribution of power absorption in each of the lower limb joints**.**

In this diagram, (a) represents FW; (b) represents BW; the white colour represents the ankle joint; the light grey colour represents the knee joint; and the dark grey colour represents the hip joint.

While increasing the inclination from downhill to uphill, the contributions to power distribution were shifted systematically among the respective joints in both FW and BW. During FW, power absorption was shifted from the ankle to the knee joint, whereas in BW it was shifted from the hip to the ankle joint. During FW, power generation was shifted from the ankle to the hip joint, but during BW, power generation was from the ankle joint at all levels of inclinations and speeds.

Net joint work in the lower limb joints during FW and BW

The net joint work is used as an index to identify the resultant work of lower limb joints, which is indicative of the dominant process (the generation and/or absorption of energy) by the joint at the final point of the completed gait cycle.

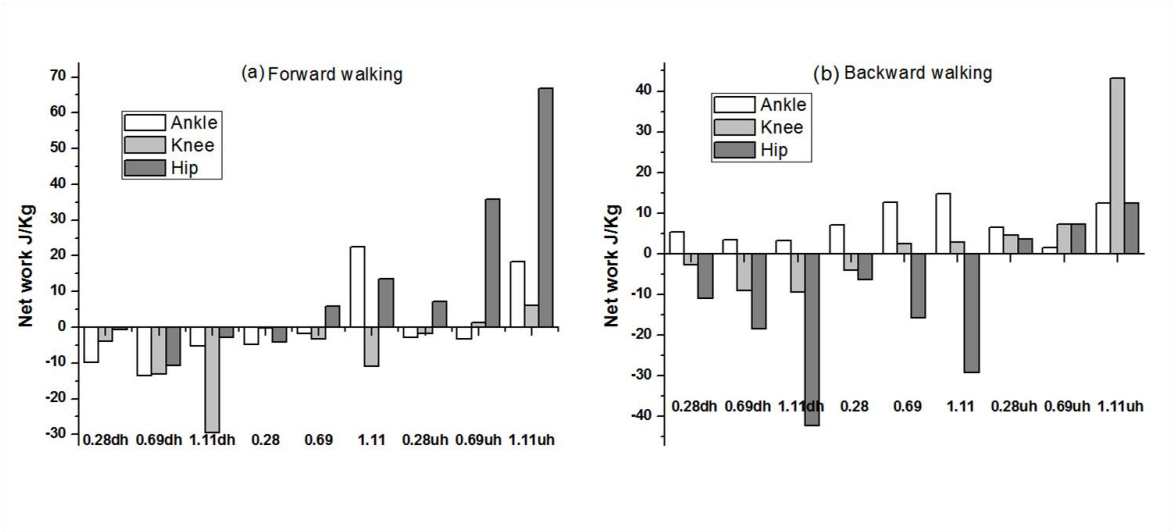


Figure 5.41 Net joint work during forward and backward walking.
In this figure (a) represents FW; (b) represents BW; the white colour represents the ankle joint; the light-gray colour represents the knee joint; and the gray colour represents the hip joint.

The joint network significantly differs among the joints in association with changes in the direction and speed of walking and the inclination. During FW (Figure 5.41a), the ankle joint network showed absorption at all inclinations and speeds except on a level surface at a speed of 1.11m/s and on an uphill incline at a speed of 1.11 m/s speed. The knee joint network showed absorption at all inclinations and speeds except in the case of walking uphill at an increased speed when power was generated. The hip joint network for downhill walking showed power absorption, while in the case of a level surface and an uphill inclination, the hip joint showed more power generation at all speeds except at the 0.28m/s speed.

During BW (Figure 5.41b), the ankle joint network generates power at all inclinations and speeds. In the case of level and uphill walking, the knee joint network proved itself to be capable of greater power generation, whereas downhill walking brought with it power absorption at all speeds. The hip joint network in the uphill phase of walking was found to involve power generation instead of power absorption at all three of the speeds.

Total work during FW and BW walking

The total work of a joint is calculated by adding the sum of the numerical value of positive and negative work. Total work refers to the total energy flow in a joint during FW (Figure 5.42a) and BW (Figure 5.42b). In FW, the ankle joint showed higher energy flow in walking downhill and on a level surface. This energy was found to shift to the hip joint during uphill walking. In BW, the energy flow in a joint proved to be just the opposite of that observed in FW. In BW, the energy flow in the hip joint was found to be dominant in downhill walking. It then shifted to the ankle joint when walking took place on a level surface and on an uphill walking.

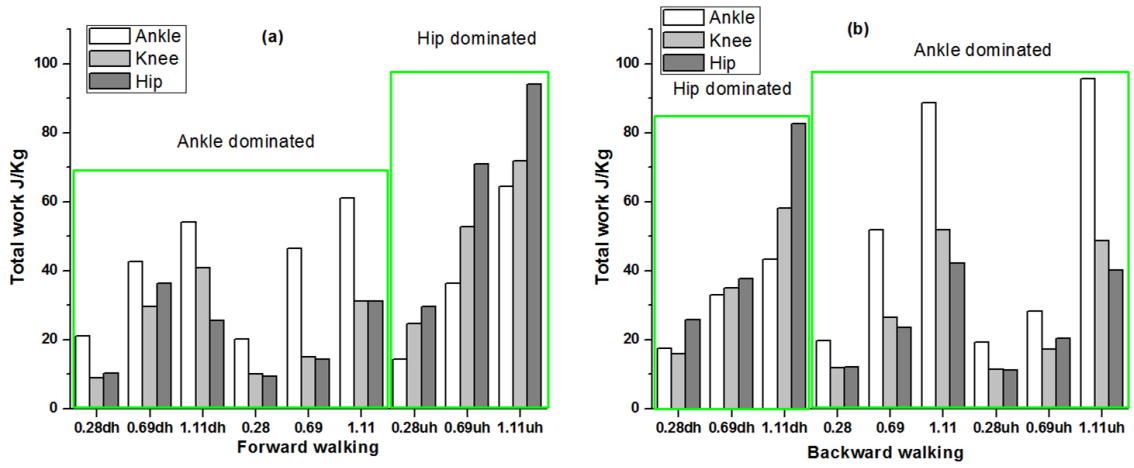


Figure 5.42 Total work during forward and backward walking

In this figure, (a) represents FW; (b) represents BW; the white colour represents the ankle joint, the light-gray colour represents the knee joint; and the gray colour represents the hip joint.

Muscle activity

Among the 92 simulated muscles in the anthrometric model, seven key muscles were chosen for studying the hip, knee and ankle joints. The activity levels of three hip joint muscles (the GM, the Gmed, and the IL), of two biarticular muscles used in both the hip and the knee joint (the RF and the BF), and of two ankle joint muscles (the TA and the LGAS) were plotted for

analysis. Figures 5.43 to 5.47 present muscle activities associated with speeds and inclinations, while Table 5.15 shows the statistical comparison.

Gluteus maximus: Figure 5.43 compares the activity levels of the GM muscle for FW and BW at all three of the levels of inclination and speed.

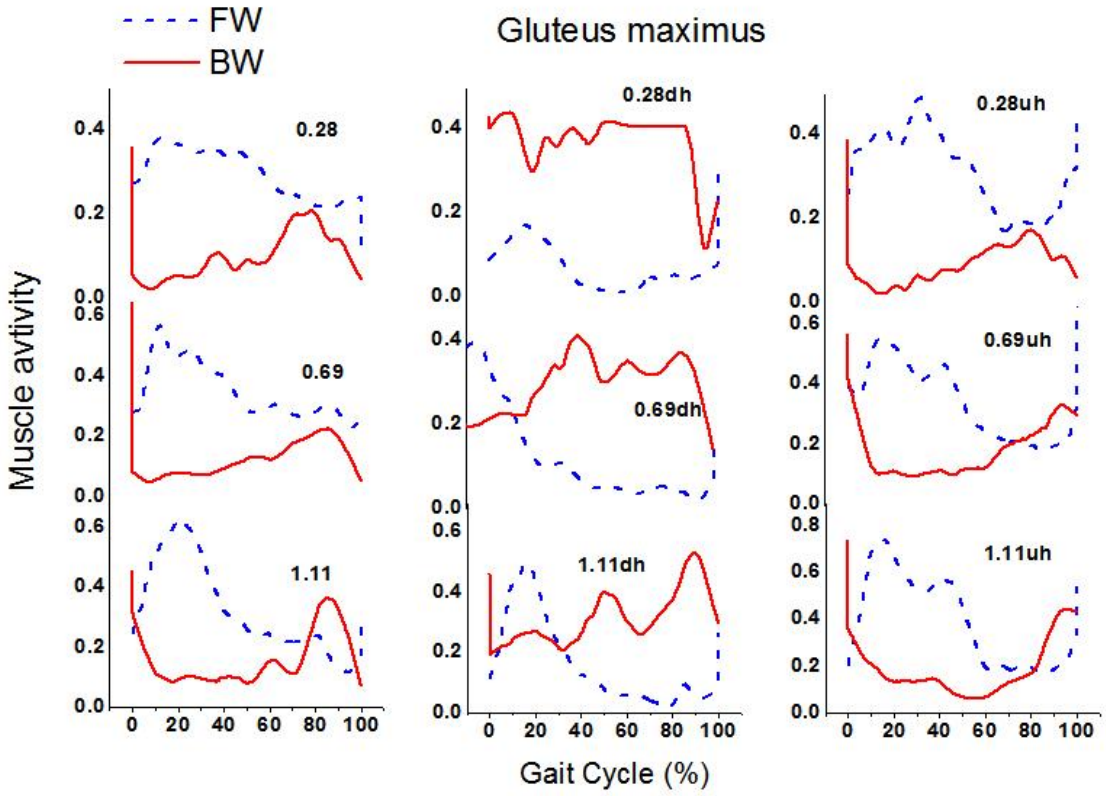


Figure 5.43 Gluteus maximus muscle activity during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The activity levels for the GM muscle at all speeds and inclinations showed opposite trends during FW and BW. During FW on a level surface and on an uphill inclination, intense muscle activity occurred from the heel strike to the terminal-stance phase. This gradually declined up to the swing phase, while the opposite occurred during BW. During downhill BW, activity by the GM muscle was more intense than that for these muscles during FW on a downhill inclination.

Gluteus medius: Figure 5.44 shows comparison for the activity levels of the Gmed muscle for FW and BW respectively at all inclinations and at each speed

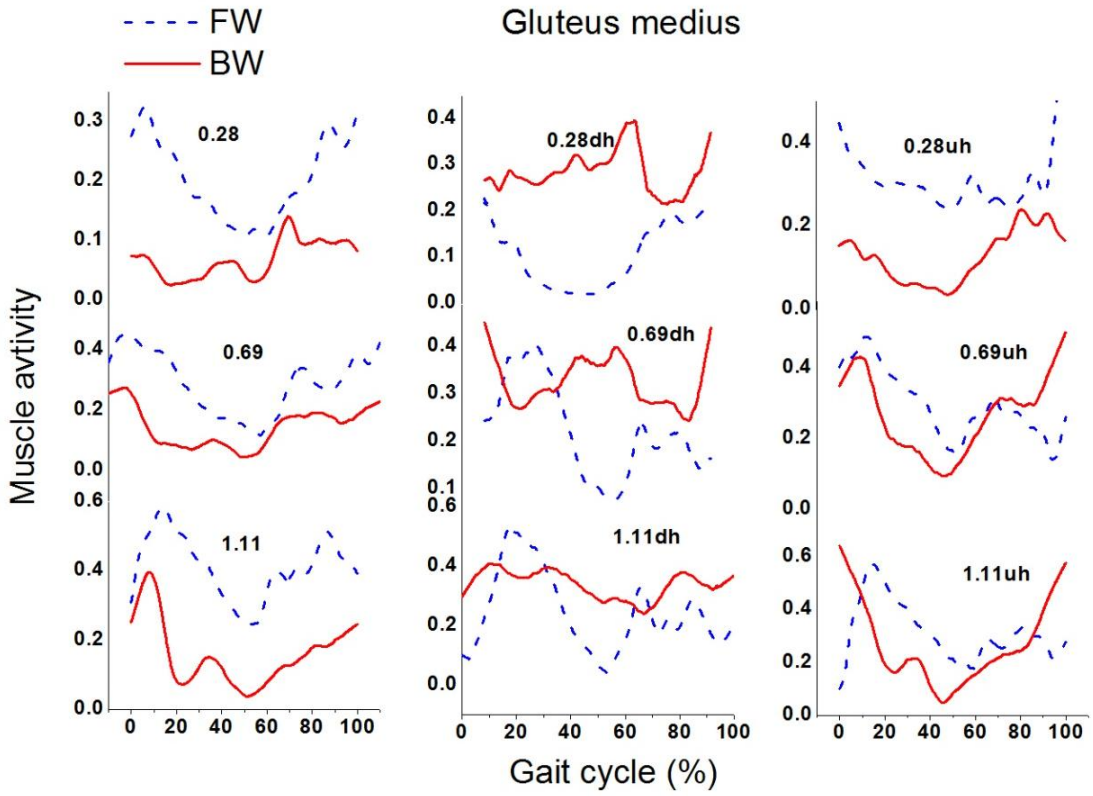


Figure 5.44 Gluteus medius muscle activity during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

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The activity level for the Gmed muscle during BW on a level surface and on an uphill inclination showed less muscle activity than was the case during FW. The Gmed muscle was more active on the downhill inclination for an entire gait cycle during both FW and BW.

Iliacus: Figure 5.45 shows comparison of the activity levels of the IL muscle during FW and BW at all levels of inclination and at each speed.

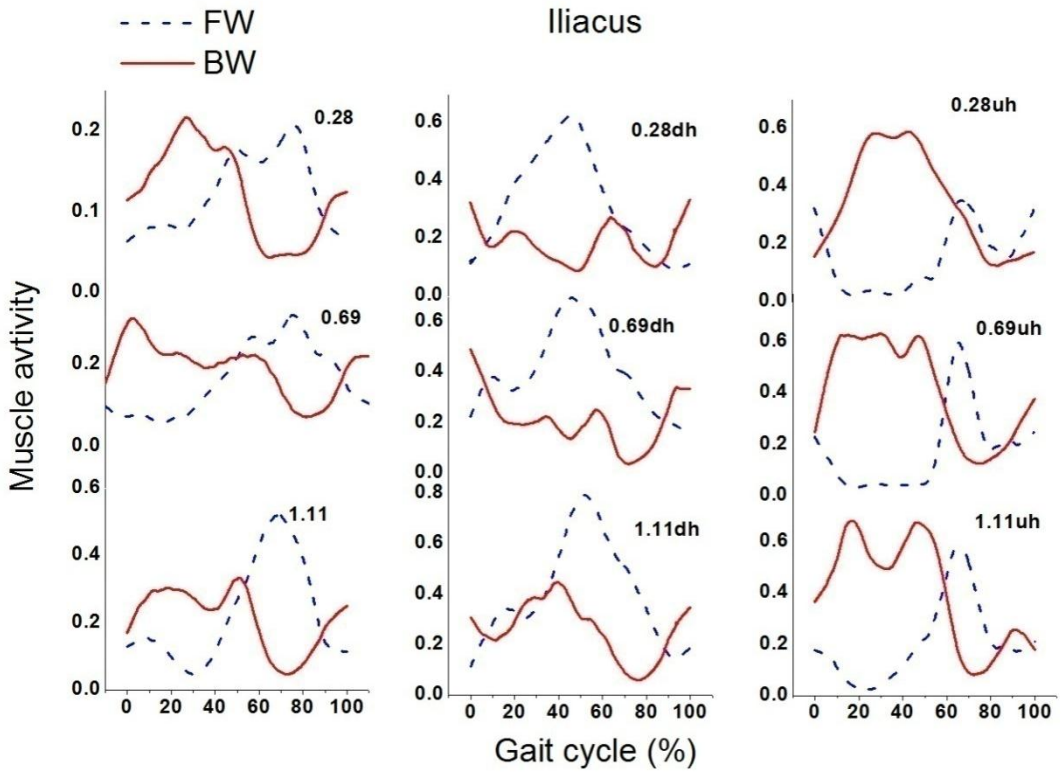

Figure 5.45 Iliacus muscle activity during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The activity levels for the IL muscle showed opposite trends at all speeds and inclinations during FW and BW. Downhill FW showed greater muscle activity than in the case of downhill BW. The opposite occurred in uphill walking. During FW, peak muscle activity occurred during the terminal stance phase, whereas during BW peak muscle activity occurred throughout the entire stance phase.

Biceps femoris: Figure 5.46 shows comparison of the activity levels of the BF muscle for FW and BW at all inclinations and at each speed.

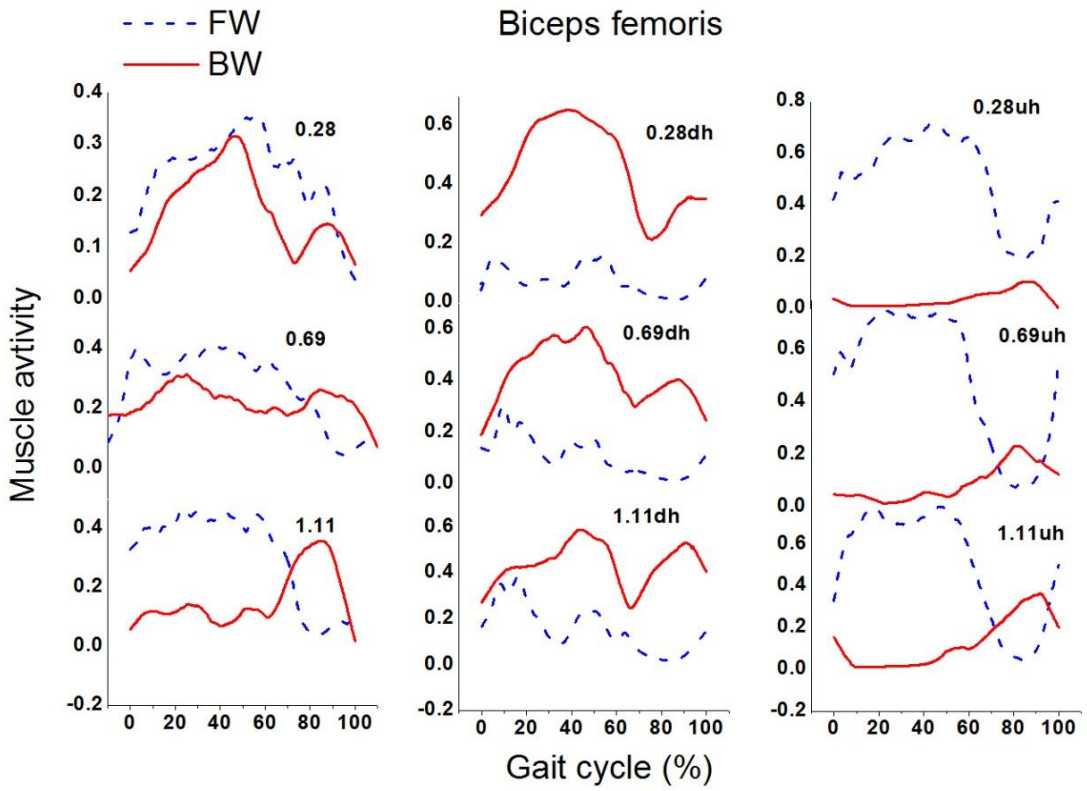

Figure 5.46 Biceps femoris muscle activity during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s

The most intense activity occurred in the BF muscles during both FW and BW on a level surface and at a speed of 0.28m/s. The muscle activity levels for FW and BW differed at the other speed levels. During FW on a level surface, the BF muscle was more active in the stance phase than was the case with the activity levels of these muscles during BW. On the downhill inclinations, the activity levels of the BF muscles were more intense than was the case with the activity levels of these muscles during FW, where their lesser activity was pronounced. The opposite occurred in uphill walking at all speeds.

Rectus femoris: Figure 5.47 shows comparison of the RF muscle activity for FW and BW respectively at all three levels of inclination and at each speed.

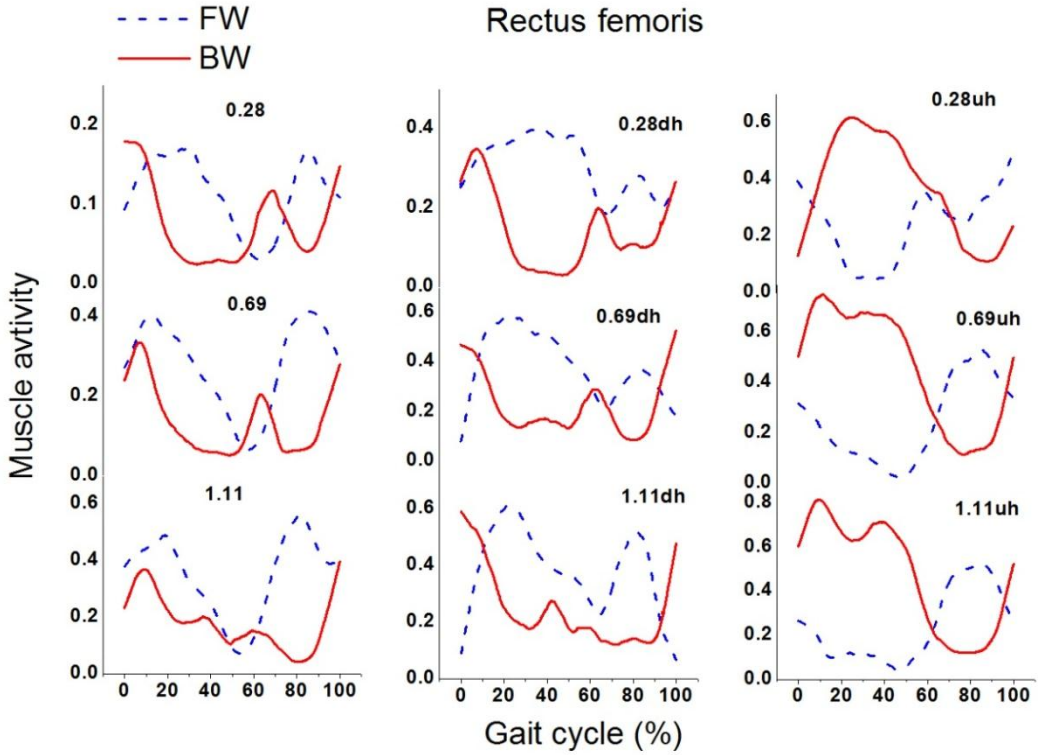

Figure 5.47 Rectus femoris muscle activity during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The activity levels of the RF muscle showed opposite trends for FW and BW respectively at all inclinations and speeds. Similar activity levels were observed during forward and backward walking on a level surface but the magnitude of muscle activity was less in BW than it was in FW.

Tibialis anterior: Figure 5.48 shows comparison of the activity levels of the TA muscle for FW and BW at all three levels of inclination and at each speed.

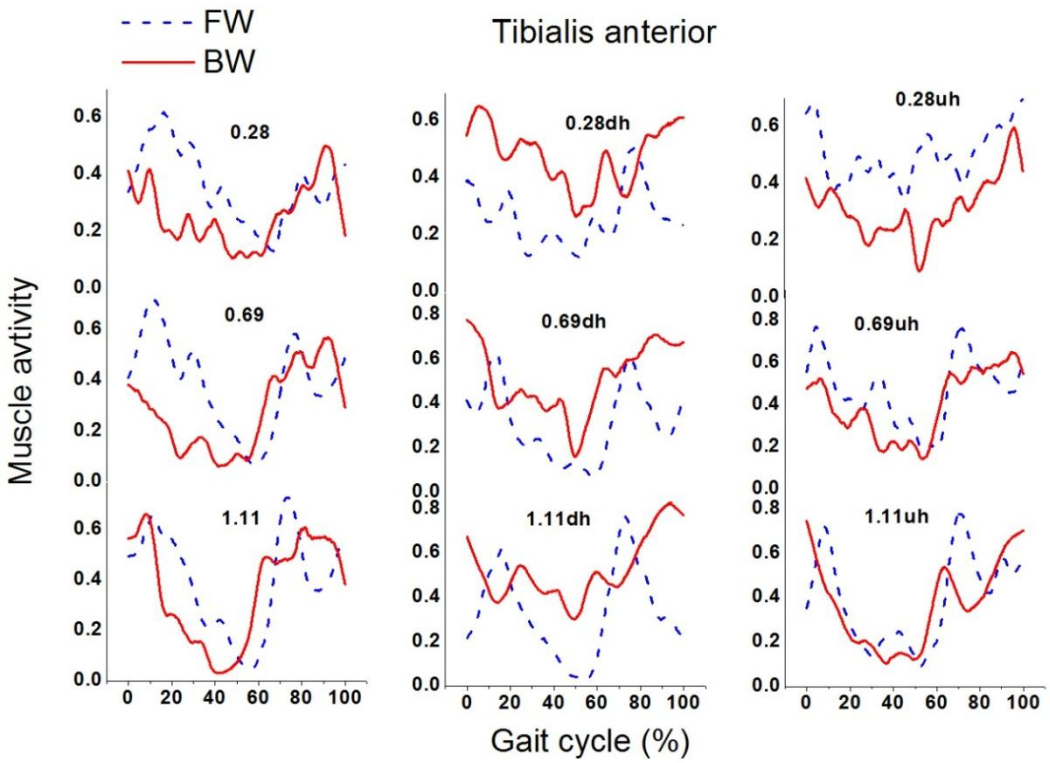

Figure 5.48 Tibialis anterior muscle activity during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The TA muscle showed greater activity in both forward and backward walking. Specifically, these muscles showed greater activity during the BW on a downhill slope than was the case with these muscles during FW.

Lateral gastrocnemius: Figure 5.49 shows comparison of the activity levels of the LGas muscle on for FW and BW respectively for all three of the levels of inclination and speed

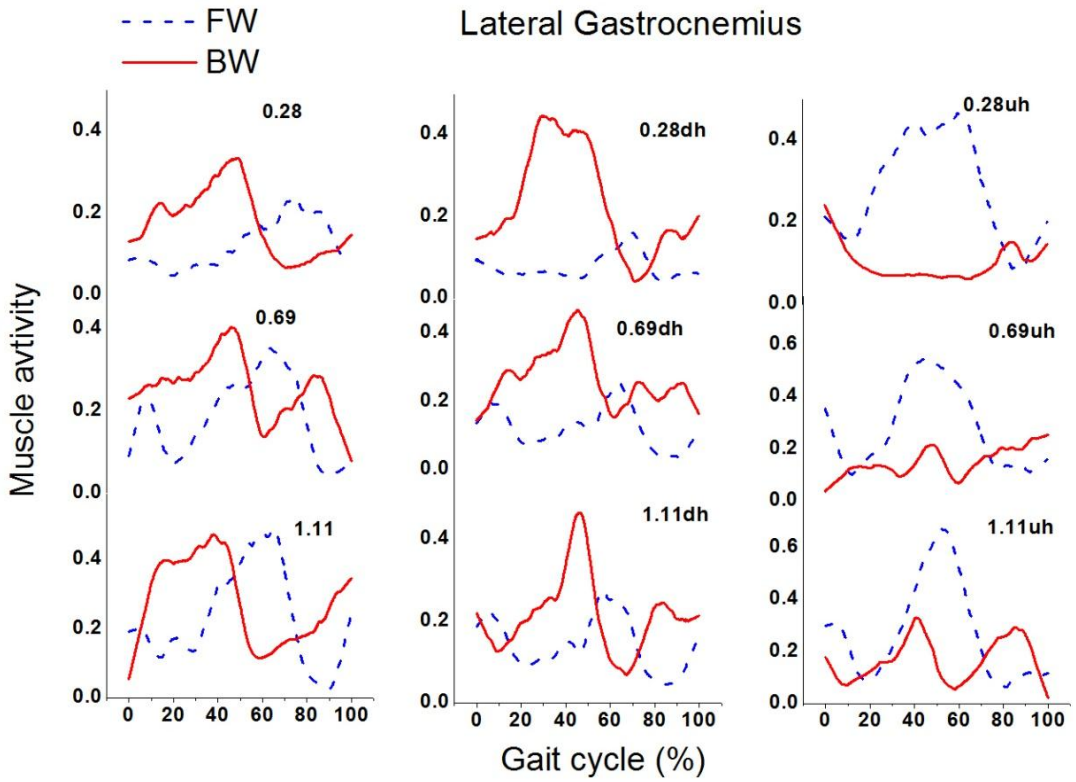

Figure 5.49 Lateral gastrocnemius muscle activity during FW and BW at the three respective levels of inclination and speed.

Blue line: FW; red line: BW; dh: downhill; uh: uphill; the value 0.28, 0.69 and 1.11 represent the walking speed in m/s.

The activity levels of the LGas muscle showed similar trends in both FW and BW. During FW on an uphill slope, the LGas muscle showed more intense activity than was the case with the activity levels of these muscles during BW. By way of contrast, FW on a downhill slope showed less activity in the LGas muscles than in these muscles during BW.

Statistical comparison of muscle activity patterns for forward and backward walking at varying speed and at all three levels of inclination

Table 5.15 presents muscle activity during FW/BW at the three levels of inclination and speed. The one-way ANOVA p-value was used to calculate the significance of the difference between the muscle activity levels for all inclinations and speeds. In this study, $p < 0.05$ and $p < 0.001$ shows a statistically significant difference between the gait cycles. The correlation coefficient

(r-value) was calculated to establish the relationship between the levels of muscle activity at the respective inclinations and speeds.

Table 5.15 Comparison of muscle activity between FW and BW for three levels of inclination and speed.

Muscle activity	FW/BW Inclination	FW/BW speed					
		0.28 (m/s)		0.69 (m/s)		1.11 (m/s)	
		r	p	r	p	r	p
Gluteus maximus	0%	0.77	<0.001	0.88	<0.001	0.60	<0.001
	-5%	-0.25	<0.001	0.55	<0.001	0.75	<0.001
	+5%	0.88	<0.001	0.44	<0.001	0.04	<0.001
Gluteus medius	0%	0.25	<0.001	0.70	<0.001	0.59	<0.001
	-5%	-0.42	<0.001	-0.47	<0.001	0.24	<0.001
	+5%	0.30	<0.001	0.31	<0.001	0.04	<0.001
Iliacus	0%	-0.58	0.79	-0.70	<0.001	-0.74	<0.05
	-5%	-0.45	<0.001	-0.25	<0.001	0.14	<0.001
	+5%	-0.71	<0.001	-0.77	<0.001	-0.58	<0.001
Biceps femoris	0%	0.72	<0.001	0.33	<0.001	-0.80	<0.001
	-5%	0.52	<0.001	0.30	<0.001	-0.001	<0.001
	+5%	-0.82	<0.001	-0.95	<0.001	-0.92	<0.001
Rectus femoris	0%	-0.11	<0.001	0.21	<0.001	0.10	<0.001
	-5%	-0.33	<0.001	-0.44	<0.001	-0.24	<0.001
	+5%	-0.81	<0.001	-0.81	<0.001	-0.83	<0.001
Tibialis anterior	0%	0.25	<0.001	0.31	<0.001	0.57	<0.001
	-5%	0.13	<0.001	0.48	<0.001	0.21	<0.001
	+5%	0.49	<0.001	0.65	<0.001	0.66	<0.001
Lateral gastrocnemius	0%	-0.62	<0.001	-0.02	<0.001	-0.29	<0.001
	-5%	-0.50	<0.001	-0.21	<0.001	-0.32	<0.001
	+5%	-0.72	<0.001	-0.25	<0.001	-0.14	<0.001

Level walking: 0%; downhill: -5%; uphill: +5%; slow speed: 0.28m/s; medium speed: 0.69m/s; fast speed: 1.11m/s; Pearson's correlation coefficient, "r", and the ANOVA "p" value.

Comparison of the muscle activity associated with the respective hip, knee and ankle joints during FW and BW at all inclinations and speeds, showed that there were negative correlation for some of the variables that were compared (e.g. while FW showed more intense muscle activity, at the same time BW showed less muscle activity (or *vice versa*)). Some of the variables that were compared showed strong positive correlation because FW and BW were either associated with more intense activity or with less activity. Other value showed weak positive correlation because, under certain conditions, FW would be associated with greater muscle activity than BW (or *vice versa*). The p-value showed the significance of the difference in muscle activity at all inclinations and speeds.

5.5 Discussion

Joint kinematics and kinetics arise as a result of muscle contractions, which occur in accordance with a selected neural control strategy. Therefore, changes in the patterns of joint mechanics can provide insight into changes in the strategy employed by the nervous system to control movement. The results from the previous section are discussed at this stage in three types of comparison, namely within FW, within BW, and between FW and BW all in terms of inclinations and speeds.

5.5.1 Kinematics and kinetics of FW at the three levels of inclination and speed

Joint kinematics: The joint angle pattern showed a strong correlation (Table 5.3) with all of the three levels of inclination and speed. These patterns confirm the previous reports concerning walking on a level surface and on an uphill inclination (111,113,172). The study showed that in FW an increase in speed is associated with a longer step length and a larger total ROM. Although the level of inclination has little effect on the total ROM, the angle of the joint in question shows distinct changes in flexion and extension movement during the specific phases of the gait cycle (Figure 5.17).

In the case of walking uphill, hip flexion, knee flexion and ankle dorsiflexion were observed. In contrast, walking downhill, brought with it hip extension, increased knee flexion and ankle plantar flexion in the stance phase. These distinct changes in the kinematic parameters lead to the propulsion of the body to chase the centre of gravity, with controlled postural stability to compensate for the surface inclination.

Joint kinetics: Joint kinetics includes joint moment, joint power and muscle activity. These three components of joint kinetics are inter-related to produce movement during walking. In treadmill walking, the external force created by the moving belts is neutralised by internal muscle force to maintain the stability of the body. The net forces from these internal and external forces generate a moment and power in the lower limb joints for the movement of the body. Hence, the calculated positive moment is indicative of joint extension movement, while the calculated negative moment is indicative of joint flexion movement. Positive power assumes the generation of power in a joint as a result of the concentric contraction of the muscle, whereas negative power assumes the absorption of power as a result of the eccentric contraction of the muscle (1).

In FW, an increase in the speed of walking at all inclination results in larger magnitudes of moment (Figure 5.18), power (Figure 5.19) and muscle activity (Figures 5.20 to 5.22) in the lower limb joints (hip, knee, and ankle). The raised levels of these kinetic parameters show that higher speed levels are required for more kinetic energy to be dissipated in the joints. These observations are consistent with the existing reports for walking on a ramp (18,113,170,172).

A change in the level of inclination at all speeds allows for the magnitude of the kinetic parameters to be increased for uphill and downhill rather than for level walking in order to compensate for the gravitational force. Although the magnitudes of the kinetic parameters were increased for downhill and uphill walking, the moment and power patterns were found to be inversely correlated for the hip and knee joints. In uphill walking, the hip joint produces extensor moment while the knee joint produces flexor moment. Opposite moment patterns were observed in downhill walking. Observations were made of the plantar flexor moment in the ankle joint at all inclinations and speeds.

The differences in joint activities with respect to inclination were also observed in joint power. The hip, knee and ankle joints exhibited greater expenditure of power in both uphill and downhill walking. The reader is referred to section 5.5.3.2 where aspects of power generation and absorption are discussed separately. In essence, the changes in inclination require the power in a joint to catch up the gravitational push/pull effect which is achieved through a trade-off between the flexors and extensors of the hip and knee joints. Hence, the kinetic and kinematic properties of a joint are indicative of different control strategies used in uphill and downhill walking.

The simulated muscle activity presented in this study supports this notion. In general, this study found that an increase in speed and inclination generates greater muscle activity. Although, specific observations were made in respect of uphill and downhill walking, the simulated muscle activity suggests that during uphill walking, the BF, GM and LGAS muscles are more active, delivering greater magnitudes of moment and power, which are of longer duration.

In contrast, in the case of downhill walking, the IL, RF, and TA muscles were found to be significantly active. Hence, a different set of flexor and extensor muscles is controlled by the neural network to establish gait stability in uphill and downhill walking.

5.5.2 Kinematics and kinetics of BW at the three levels of inclination and speed

Joint kinematics: The joint angle patterns for BW were found to be strongly correlated for all three of the inclinations and speeds. These patterns confirm previous reports on inclined walking on level surfaces and uphill inclinations (22,24,48). Backward walking shows that by increasing the speeds, there is an associated increase in the step length and the total range of motion (ROM). Though inclination has little effect on the total ROM, the joint angle showed distinct changes in flexion and extension movement at specific phases in the gait cycle (Figure 5.23).

In the case of backward uphill walking, observations were made of hip extension, greater knee flexion in the swing phase, and ankle dorsiflexion. In the case of backward downhill walking, observations were made of hip flexion, lower levels of knee flexion in the swing phase, and ankle dorsiflexion in the stance phase. These changes in the kinematic parameters presume to propel the body to chase the centre of gravity, with controlled postural stability to compensate for the surface inclination.

Joint kinetics: During BW on a treadmill, the external force created by the moving belts of the machine is e neutralised by the internal muscle force of the body to maintain its stability. In BW, an increase in the speed at all inclinations shows greater moment (Figure 5.24), generates more power (Figure 5.25) and increases muscle activity (Figures 5.26 to 5.28). These raised kinetic parameters show that the higher the speed, the greater the amount of kinetic energy required in the joints. Similarly, to compensate for the energy requirements associated with the gravitational force, the absolute value of the kinetic parameters increased for BW on an uphill inclination rather than for BW on a level surface and on a downhill inclination. Although the absolute value increased, the moment and power patterns for backward uphill and downhill walking were found to be inversely correlated in the case of the hip and knee joints.

In backward uphill walking, the hip joint produces flexor moment, whereas the knee joint produces extensor moment. Opposite moment patterns were observed in backward downhill walking. Furthermore, observations were made of plantar flexor moment in the ankle joint at all inclinations and speeds.

The differences in joint activity with respect to changes in inclination were also observed in joint power. The hip, knee and ankle joints exhibited the ability to generate maximum power on uphill inclination and to absorb maximum power on level surfaces and downhill inclination. The aspects of power generation and absorption are discussed separately in Section 5.5.3.2.

In essence, the changes in inclination require that a joint should have the power to catch up the gravitational push/pull effect which is achieved through a trade-off between the flexors and extensors of the hip, knee and ankle joints. Hence, the kinetic and kinematic properties of a joint are indicative of different control strategies, which are used in backward uphill and downhill walking. The simulated muscle activity presented in this study supports this notion. In general, an increase in speed and inclination was found to generate greater muscle activity. Although specific observations were made in respect of backward uphill and downhill walking, the simulated muscle activity suggests that during backward uphill walking, the IL, RF and TA muscles are more active, delivering greater magnitudes of moment and power, which are also of longer duration.

In contrast, in the case of backward downhill walking, the GM, GMed, BF, TA, and LGAS muscles were found to be significantly active. Hence, a different set of flexor and extensor muscles was found to be controlled by the neural network in order to establish gait stability in uphill and downhill walking.

5.5.3 Comparison of the kinematics and kinetics during FW and BW at the three levels of inclination and speed

In earlier sections, FW and BW were discussed separately to reveal different neural control strategies for uphill and downhill walking. In this section, however, FW and BW are compared to investigate the requirements of neural control strategies that are regulated by the direction of walking.

Joint kinematics: The joint angle patterns for FW and BW are strongly correlated (Table 5.12) with all of the levels of inclination and speed. Although the existing literature is lacking in comparative studies of FW and BW on an inclined treadmill, Lay et al (173) made a comparative study of FW and BW by using a ramp in order to incorporate the level of inclination as an important regulator in influencing joint angle patterns. Many literature sources have compared FW and BW but without giving due consideration to the inclination factor (23,39,82,97).

The patterns revealed in this study are consistent with those reported in the literature. In walking on a level surface, the angular displacement patterns of the hip, knee, and ankle for FW and time-reversed BW were found to change marginally for the various gait phases. Backward walking on a level surface (0%) showed increased ankle dorsiflexion during the loading-response phase, and decreased knee flexion and hip flexion in the pre-swing phase at a medium speed (0.69m/s) and a fast speed (1.11m/s) as opposed to these aspects in FW (Figures 5.30 to 5.32).

However, at a slow speed (0.28m/s), the results were almost the same for both forward and backward walking. In the case of uphill BW, reduced hip flexion, monotonic knee flexion and ankle plantar flexion were similar to these same aspects in uphill FW. However, during downhill BW, more hip flexion, decreased knee flexion in the swing phase, and ankle dorsiflexion, were found to be comparable with those same aspects in FW. Such changes in the joint angles are required to raise the limb for toe clearance to heel strike. Hence, BW on a level surface shows the mirror image of FW on a level surface and it may be controlled by the same neural circuit.

Joint kinetics: Walking forward and backward requires opposite mechanical movements in the lower limb. In humans, the constraints in the lower limb joints and visual cues result in complicated patterns in BW which cannot be interpreted as a simple reversal of those manifesting in FW. Hence, BW, as a locomotive task, requires an additional signal from the central pattern generator in the neural network.

It is interesting to recall the observations made in the previous section to the effect that walking on an inclined surface requires a different set of kinetic parameters from those required by the hip and knee joints with irrespective of the direction of walking. Observations from this study show that the moment patterns (Figures 5.33 to 5.35) and muscle activity levels (Figures 5.43 to 5.49) in the hip and knee are similar for FW uphill and BW downhill and for FW downhill and BW uphill. In this study, in FW uphill and BW downhill, the hip joint showed extension moment while the knee joint showed flexion moment.

The biarticular muscle BF was active in both types of walking to produce the concentric contraction of the BF muscle to produce flexion moment in the knee and extensor moment in the hip at the stance phase. At the same time, the single articular muscles GM and LGAS were also active in supporting the extension of the hip and plantar flexion in the ankle respectively. Similarly, biarticular muscle RF was active in FW downhill and BW uphill with hip flexion and

knee extension moment at the stance phase. Additionally, the single articular muscle IL was active in supporting hip flexion. The Gmed and TA muscles did not follow any specific pattern.

By considering these similar hip/knee joint moment and muscle activities, we cannot conclude that both FW uphill and BW downhill or FW downhill and BW uphill are controlled by the same neural network since the power patterns are distinctly different. Hence, in both of these cases, joint power requirements are an important factor in determining the various control strategies.

In the next section, in order to understand the movement demands in a gait cycle, we examine the power distribution among the lower limb joints.

Power distribution in the hip, knee and ankle joints

In the process of walking, power is released by the ankle, knee and hip joints. A study of the distribution of power among the joints is essential to determine the muscle activity during walking. In the process of walking in a specific direction at a specific speed and at a specific inclination, there are certain influencing factors that come into play causing power generation/absorption in the hip, knee and ankle joints respectively (174).

A statistical analysis of the power profiles for FW and BW shows an inverse correlation and a significant level of difference (<0.05) between the FW and BW at all inclinations and speeds. This inverse power flow in the joints is manifested in an execution of joint movement in BW that is directly opposite to that in FW. Since the power experienced in a joint results from muscle activity, the eccentric contracted muscle causes concentric contraction, or *vice versa*, when the walking direction changes. In the meantime, the faster locomotion embraces greater joint moment and higher angular velocity, irrespective of the direction of walking. Hence, greater power is achieved across the hip, knee and ankle joints (Table 5.14) is a good illustration of this phenomenon in both FW and BW. The balance and postural stability during walking on an inclined surface further changes the distribution of power.

This study identifies the difference in the distribution of the total power expenditure among the joints for FW and BW. The positive energy distribution during FW (Figures 5.39 and 5.40) was found to be largely delivered at the ankle joint on downhill inclination and on level surfaces at all speeds. This is positively associated with positive muscle work during the stance phase and is primarily provided by the plantar flexors in the ankle (153,171,175). During uphill walking, the joint power shifts from the ankle to the hip and this was found to be the case across all of

the walking speeds. This is positively associated with the hip, where the extensor muscles generate more positive power to propel the body forward in uphill walking (176,177).

The ankle contributed a greater output of negative power (Figure5.40) than that contributed by the knee and hip at walking speed of 0.28 and 0.68 m/s respectively in downhill and level-surface walking. In uphill walking and at a top speed of 1.11 m/s, the percentage contribution by the knee proved to be more. Overall, during FW on a level surface and on a downhill inclination, the power tends to be predominantly generated at the ankle. It was found in this study that with an increase in speed, the contributions of power by the ankle and hip increase whereas those by the knee decrease.

During uphill walking, the hip is the dominant joint in generating power. This clearly indicates the demanding task of drawing the power from the hip joint. As in the case of power generation, the absorption of power is dominated by the ankle during downhill and level-surface walking. At higher speed and on uphill inclines, the hip contributes more power than the knee. Hence, the contribution by the hip was found to be significant in terms of both energy generation and shock absorption in the process of carrying out the demanding task of walking.

The average value for positive and negative power during BW has not yet been reported. Hence, there is no comparative study of BW and FW in this respect. Figures 5.39 and 5.40 show the average positive power during BW is largely generated at the ankle joint. This finding suggests that power generated during the stance phase is mainly from the plantar flexors of the ankle to catch the centre of mass in BW.

The distribution of negative power (Figures 5.39 and 5.40) in BW shows a systematic shift from the hip on a downhill incline to the ankle on an uphill incline. The shifts in energy absorption suggest that the deceleration of the body in the swing phase of the gait cycle is achieved by the different joints in accordance with the level of inclination.

To understand the results, the reader is referred to Figure 5.42, which is a good illustration of walking on an inclined surface. This figure shows that at the stance phase, FW uphill and BW downhill are in similar posture, with the backward positioning of the hip as opposed to the forward leaning of the head. On the other hand, during FW downhill and BW uphill the trunk is erect.

These similarities were quantitatively confirmed through the calculation of total workflow in the joints. The ankle was found to be dominant during both FW uphill and BW downhill. Conversely, the hip joint was found to be dominant during both FW downhill and BW uphill. These observations clearly indicate that the inclination of the walking surface determines the

contribution of the joints to the total work rather than the speed at which the walking takes place.

Although this researcher found that similarities in the total workflow in the joints depend on the posture, the direction in which walking takes place affects the respective proportions of positive and negative power. Figure 5.41, the network of joints shows that the absorption of power by all of the joints is greater than the generation of power in FW on a downhill inclination. This necessitates the deceleration of walking on the treadmill to compensate for the kinetic energy that is supplied from the moving belt, whereas an increase in the inclination demands that energy be generated to supply the required power for walking. In all of the cases, walking backwards requires a more positive energy flow in the ankle irrespective of the speeds and direction of walking. Even though total workflow shows that the hip dominates in BW downhill, the ankle supplies more positive power than the hip.

5.6 Conclusion

The significance of this work lies in exploring the biomechanical relationship of speed, inclination, and direction of walking. Integrating the kinetic and kinematic observations provides insight into the way in which neural control strategies adapt for locomotive tasks.

1. Walking speeds is directly related to energy requirements. Increasing the speed requires higher magnitudes of joint moment, joint power and muscle activity, irrespective of inclination and the direction of walking.

2. In forward and backward walking, uphill and downhill tasks produce opposite joint moment with the different contributions of the respective sets of flexor and extensor muscles. These indicate that the motor control task requires different control strategies for inclined walking.

3. In considering the direction of walking, the kinetic parameters did not emerge as mirror images for FW and BW. Anatomical constraints and visual cues were additional considerations in the biomechanical parameters of BW. Hence, a simple time reversal is not sufficient to distinguish between BW and FW. The similarities were observed between FW uphill and BW downhill; and between FW downhill and BW uphill in the hip/knee joint moment and muscle activity. During FW uphill and BW downhill, for instance, the hip joint showed extension moment and the knee joint showed flexion moment. The biarticular muscle BF was found to be active in both types of walking. However, we cannot conclude that both were controlled by the same neural network since the power patterns were distinctly different.

4. The distributions of total power flow among joints were found to be related to the posture associated with the level of inclination in both FW and BW. The ankle contributes more in both FW uphill and BW downhill (a leaning trunk), whereas the hip dominates for FW downhill and BW uphill (an erect trunk). On a level surface, the ankle dominates in both FW and BW irrespective of the walking speeds. The ankle joint was found to be the main source of propulsion at all inclinations and speeds during FW and BW. The only exception was in the case of FW uphill.

CHAPTER 6 – General conclusions

6.1 Conclusions

The general conclusions of the present thesis included that, BW training is clinically effective and its biomechanical characteristics require additional neural control strategies which may enhance rehabilitation benefits in neuromuscular gait impairment conditions. The conclusions from two systematic reviews (Chapter 3 and Chapter 4) and experimental studies (Chapter 5) are summarised below.

To establish the effectiveness of BW in musculoskeletal and neurological gait impairment conditions in the form of a systematic review

In this systematic review, the literature on the effectiveness of BW in the treatment of gait impairment conditions was systematically reviewed. The systematic review included eight randomised and quasi-randomised controlled studies from the existing literature. In all included studies, the main intervention was BW as a rehabilitation strategy in the management of the musculoskeletal and neurological gait impairment conditions. The identified eight studies dealt with knee osteoarthritis, stroke and diabetic peripheral neuropathy. The outcomes were synthesised through meta-analysis for clinically homogeneous studies. The SMD values were calculated for individual studies without estimating overall effect for clinically heterogeneous trials. The results show that the addition of BW with CPT was significantly effective in reducing knee OA related pain (total SMD: -0.87), lowering the functional difficulties (total SMD: -1.39) and improving muscle strength (SMD: 1.51). In stroke patients, BW with CPT enhances step time and balance. Though there are no direct clinical outcomes in DPN patients, BW training produces uniform plantar pressure at forefoot which may be useful to increased balance. In conclusion, this systematic review suggests that BW with CPT is clinically worthwhile for the patients with knee OA.

To describe the biomechanical characteristics of BW in the form of a systematic review

In summary, the present systematic review retrieved 20 observational studies from the existing literature and compared the biomechanical properties of BW with FW. It reveals BW exhibits; lower angles for knee joint flexion and ankle joint plantar flexion reduced power in ankle and hip joint, increased muscle activity, decreased GRF and gait parameters except stride frequency

than FW. Hence, the modified neural control strategies were required to produce BW from FW. Each of these biomechanical outcomes from BW was reported for specific therapeutic benefits in rehabilitation. For eg; the average lower TFJRF during BW helps to reduce the chronic knee injuries while treating tibio-femoral joint problems. The outcome shows the benefits of BW is consistently higher than FW in different environments such as, on ground, treadmill and in water. Backward walking in water yield increased muscle activity than ground and treadmill. Moreover, the GRF indicates BW in water is safer than land for treating balance-related diseases.

To explore the kinematics and kinetics during forward and backward walking at three levels of treadmill inclination and speed analysis through musculoskeletal modelling and simulation study.

This is an experimental study includes 10 participants who performed FW and BW on an instrumented treadmill. Three inclinations and speeds were used to identify kinetic and kinematic parameters of treadmill walking.

The significance of this work lies in exploring the biomechanical relationship of speed, inclination, and walking direction. Integrating the kinematic and kinetic observations provide following conclusion,

1. Walking speeds directly related to energy requirements. Increasing speed requires higher magnitudes of the joint moment, joint power and muscle activity irrespective of inclination and direction.

2. In forward and backward walking, uphill and downhill tasks produce opposite joint moment with the different set of flexor and extensor muscles contributions. These indicate the motor control task requires different control strategy for inclined walking.

3. The kinetic were not a mirror image between FW and BW. The anatomical constraint and visual cues give additional features in biomechanical parameters of BW. Hence, a simple time reversal is not sufficient to produce BW from FW. The similarities were observed between FW uphill and BW downhill or FW downhill and BW uphill in hip/knee joint moment and muscle activities. Though, one cannot conclude both were controlled by the same neural network as power patterns were distinctly different.

5. The distributions of total power flow among joints were found to be related to the posture associated with the inclination in both FW and BW. The ankle joint had main propulsion at all inclinations and speeds during FW and BW except FW uphill.

6.1.1 Strength and limitation

Various strengths and points of significance are contained in this thesis. The two systematic reviews fill a gap in the literature in that no systematic reviews have been conducted with the purpose of understanding the biomechanical characteristics and effectiveness of BW in neuro-musculoskeletal related gait impairments. These two systematic reviews contributed to the literature by adding level 1 evidence to our scientific framework. The experimental simulation study unifies the biomechanics of walking in the aspects of direction, speed, and inclination in same experimental procedures. These kind of comprehensive studies were unavailable in literature. The findings can be used as a basis for future research and will contribute to the clinical arena.

The effectiveness of BW has been evaluated from the moderate quality studies from the existing literature. Between two systematic reviews only two meta-analyses could be performed from the available homogeneous data. Clinical heterogeneity and lack of common outcome measures among the included trials were preventing the statistical analysis. For example, CPT consists of different combinations of exercises. Moreover, the small sample sizes and lack of blinding reduce the reliability and validity of the outcomes. Hence, further research is paramount to reduce the statistical uncertainties for designing the BW combinations as an exercise programme. The biomechanical characteristics calculated from experimental studies were illustrating the overall response of the central pattern generator of a nervous system. These experimental results were inherently limited to provide associated elements of the signal sources from the complex neural circuits.

6.1.2 Recommendations for future research

In the present thesis, the clinical effectiveness of BW was found in knee OA patients. The non-randomised controlled trials and simulated biomechanical studies strongly suggest that the BW can be used in arthritis and balance related conditions. The high-quality randomised control trials are highly recommended for unbiased evaluation of clinical outcomes to knee OA patients from BW.

Forward uphill and backward downhill walking produce high activity in the same set of muscles (GM, Gmed, BF, TA, and LGas). At the same time the power calculation show that these muscles were activated concentrically (power generation) and eccentrically (power absorption) respectively. Thus, both FW uphill and BW downhill training strengthen the muscle and activate locomotor control system by different signals from the central pattern generator. Therefore, both these training might be tested together as a therapeutic intervention for Parkinson's and Cerebral palsy participants to strengthening muscle and inducing different neural circuit.

Apart from flexor/extensor properties in the sagittal plane, the study of frontal plane adductor/abductor and transverse plane internal/external rotation will give baseline data for lower limb biomechanics during FW and BW. This extensive study will assist to map the kinematic and kinetic patterns for understanding the intensity of the gait training at the specific phase of the gait cycle.

Further studies on the lower limb muscle strengthening and joint stress reduction during walking with respect to speed and inclination have to be tested appropriately for different population, such as older adults, obese people, and patients with gait impairment. In this case, both clinical outcomes and biomechanical characteristic are recommended together as important contributions to this field of research.

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Appendix – A Ethics clearance certificate

R14/49 Ms Tharani Balasukumaran

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M150116

NAME: (Principal Investigator)	Ms Tharani Balasukumaran
DEPARTMENT:	Therapeutic Sciences Wits Physiotherapy Movement Analysis Laboratory
PROJECT TITLE:	The Effectiveness and Biomechanical Characteristics of Backwards Walking
DATE CONSIDERED:	30/01/2015
DECISION:	Approved unconditionally
CONDITIONS:	
SUPERVISOR:	Dr Benita Olivier and Dr Veronica Ntsiea
APPROVED BY:	Professor P Cleaton-Jones, Chairperson, HREC (Medical)
DATE OF APPROVAL:	04/03/2015

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Secretary in Room 10004, 10th floor, Senate House, University.
I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report**.

Principal Investigator Signature _____ Date _____

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

Appendix – B Information form

Physiotherapy Department, School of Therapeutic Sciences, Faculty of Health Sciences

Wits Medical School, 7 York Road, Parktown, 2193, Johannesburg

•Tel: 847090140 • e-mail: Tharani.balasukumaran@students.wits.ac.za

Dear Students

My name is Tharani Balasukumaran. I am currently conducting a research project on the kinematics, kinetics, joint and muscle contributions during forward and backward walking at different walking speeds and inclinations. I would be most grateful if you would be willing to participate in this research project. This project is scheduled to commence in July 2016 and finish in August 2016.

Who is eligible to take part in this study?

Healthy males and females aged 18 years and above.

What are the benefits of taking part in this study?

There is no direct benefit for participating in this study and no monetary award will be given for taking part.

Why is this study important?

The aim of this study is to describe the biomechanical characteristics of backward walking (BW) on a treadmill at three levels of inclination and speed. This study is essential as backward walking is used as part of rehabilitation programmes for musculoskeletal and neurological diseases. The understanding of the muscle contribution pattern in BW at various levels and speed of treadmill walking, during BW helps to isolate and identify the particular joint and muscle activity in order to develop effective treatment plans.

What would a participant be expected to do?

Should you agree to participate, you will be asked to complete a self-administered questionnaire. You will also undergo balance and coordination tests. You will be required to wear tight black ski pants and a t-shirts, as well as to be barefoot. A gel will be put onto your skin to ensure that the electrodes stick better to the skin. Light reflective markers will be attached to pre-determined anatomical landmarks before the start of the video recordings. Electromyography activity will be recorded via surface electrodes. After the electrode placements have been determined, the skin will be prepared through shaving of the area and cleaning the area with an alcohol scrub. You will be required to walk on the treadmill for five

minutes before the start of the formal data collection. You will then walk backwards and forwards on a treadmill for40-50 minutes.

It is proposed that whole testing procedure will take approximately 1 hour 30 minutes per participant. Participation is completely voluntary and you will be free to withdraw at any time. Should you decide to withdraw from this study, no consequences will be suffered and reason for withdrawal may be withheld.

Are there any risks related to participating?

No, there are no risks involved in this study. Participant will walk forwards and backwards on the treadmill at a controlled speed. These tests are non-invasive and will not inflict any pain or discomfort.

Will information be handled as confidential?

To ensure confidentiality of participants, each student will be assigned a study number. The key to the study numbers assigned is to be kept in the possession of the researcher only. Names of participants are only to be written on the consent form and on the questionnaire. All information will be confidential and will be used only for the purpose intended in this study.

For more information on the study procedures, or if you have any queries, please phone me on 0847090140. For more information on, or for the reporting of ethical concerns, you may contact the chair of the Human Research Ethics Committee of the University of the Witwatersrand:

Prof Cleaton Jones; Tel: 011-717-2700

If you are willing to participate in this study, please complete and sign the consent form attached.

Yours truly

Tharani Balasukumaran

PHYSIOTHERAPIST& RESEARCHER

Appendix – C Consent form

I_____ hereby agree to participate in the study as described to me in the information sheet. By signing this form I am agreeing to filling in the data collection form, participate in the forward and backward walking.

I understand that there are no monetary rewards for my participation and that I am not obliged to take part and can withdraw from the study at any given time.

Email ID _____

Contact No_____

Signature _____

Witness _____

Date _____

Appendix – D Self-administered questionnaire and data collection form

* Required

For office use only
Study number:

1. Have you had any of the following? *

- ☐ Any recent fractures of lower limb and spine
- ☐ Non-treated hypertension
- ☐ Previous lower limb and spine surgery
- ☐ Any cardio vascular disease
- ☐ Obesity
- ☐ Pregnancy
- ☐ Skin allergy
- ☐ Imbalance and incoordination

2. Current Age *

_____

3. Today's date *

[At the time of completing form]

_____

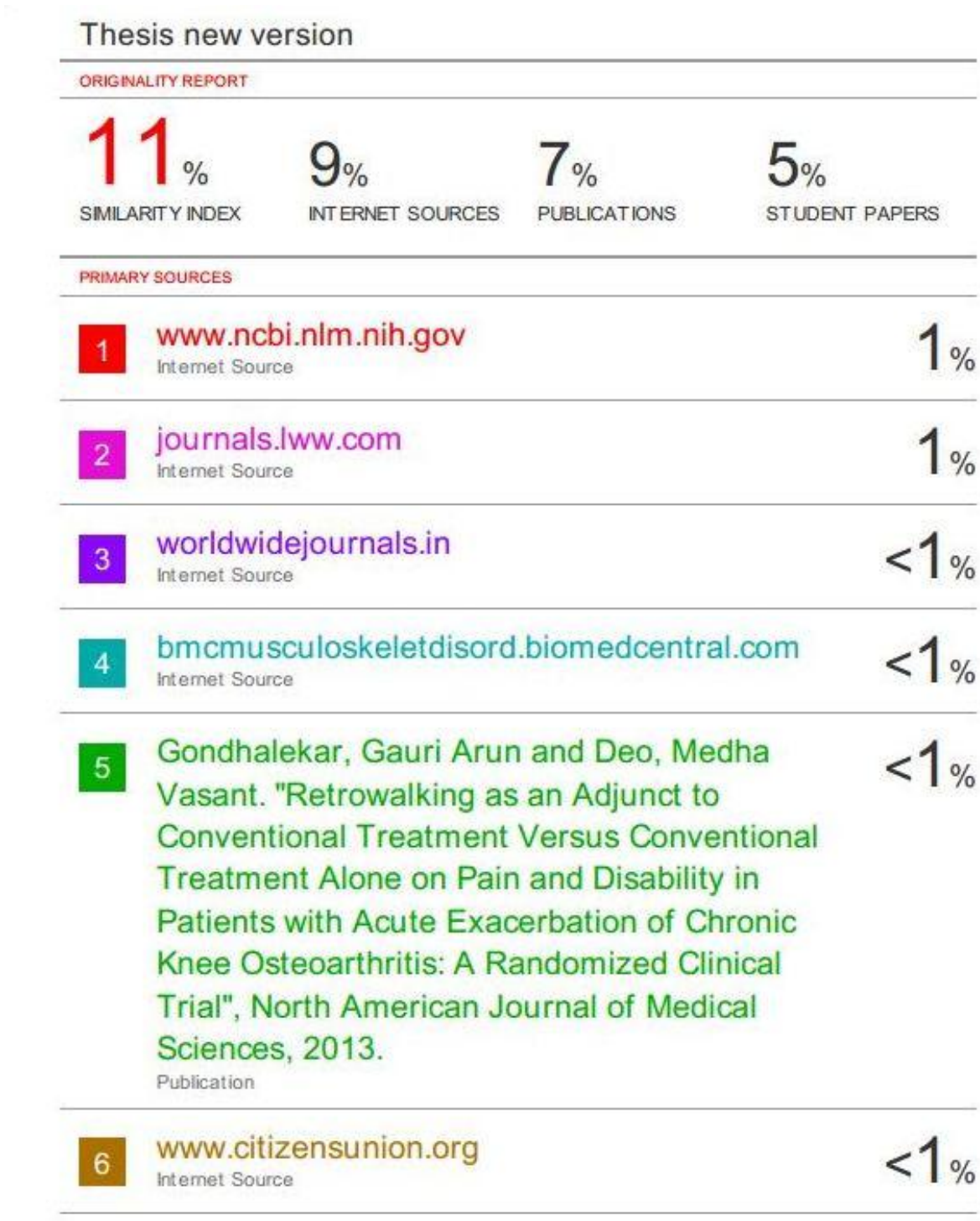
4. Gender *

- ◯ Male
- ◯ Female

Appendix – E Anthropometric measurements

Subject no		
Mass		
Height		
Foot diameter	R	L
Ankle diameter	R	L
Knee diameter	R	L
Proximal pelvis width		
Distal pelvis width		
Pelvis depth		
Marker radius		
Target radius		

Appendix – F Turnitin plagiarism report



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