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Published in:
Fire Technology

DOI:
10.1007/s10694-023-01402-x

2023

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Halder, A., Nordin, A., Miller, M., & Gao, C. (2023). Gait Biomechanics While Walking Down an Incline After Exhaustion. *Fire Technology*, *59*(4), 1833-1863. https://doi.org/10.1007/s10694-023-01402-x

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Fire Technology
© 2023 The Author(s)
Manufactured in The United States
https://doi.org/10.1007/s10694-023-01402-x

Gait Biomechanics While Walking Down an Incline After Exhaustion

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Received: 15 December 2021/**Accepted:** 27 March 2023

Abstract. This gait biomechanics study investigated stride length (SL), stride duration (SDN), the peak values of ground reaction forces ($GRFs_{peak}$), required coefficient of friction ($RCOF_{peak}$), leg joints' angles ($angle_{peak}$), angular velocity ($ang_{velx.peak}$), angular acceleration ($ang_{accx.peak}$), minimum angle ($angle_{min.}$) of the foot, and muscles' electromyography (EMG) during the stance phase (SP) of the dominant leg following an exhaustive stair ascent on a stair machine. Data were collected by a three-dimensional motion capture system synchronized with EMG and force plate while walking down a 10° inclined stationary walkway. Although the leg muscles' EMG showed no significant local muscle fatigue (LMF) during post-exhaustive walking downwards, the SL was significantly ($p < 0.05$) shorter than the pre-exhaustive. The mean vertical $GRFz_{peak.}$ was significantly ($p \leq .01$) reduced during late stance (LS) phase, however, the antero-posterior $GRFy_{peak.}$ was found to be significantly ($p \leq 0.01$) higher. The $RCOF_{peak.}$ was significantly ($p \leq .05$) higher during the post-exhaustive walking downwards, LS phase. The available coefficient of friction value of ~ 0.350 seems to be the RCOF to reduce slips and falls on an inclined dry surface. None of the post-exhaustive lower limb joints' $angle_{peak}$, $angle_{min.}$, $ang._{velx.peak}$, and $ang._{accx.peak}$ were significantly changed in post-exhaustion walking, except the knee $ang._{accx.peak.}$, which was significantly ($p < 0.05$) increased during the LS period. The constrained post-exhaustive gait biomechanics indicate a perturbed gait, which may increase the risks for slips and fall-related accidents, when walking downwards and working on slopes. However, the non-significant joint angle changes

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imply that walking down is less demanding in a kinesiological perspective compared to walking up an incline.

Keywords: Localized muscle fatigue, Fall accidents, Incline gait biomechanics, Required coefficient of friction, Gait ground reaction forces, Electromyography

Abbreviations

AMP	Amplitude of the muscle activity on electromyography data
BLa^{-}	Blood lactate (mmol l^{-1})
EMG	Muscle electromyography
FC	Final contact, toe-off, the end time of the stance phase
GRF	Ground reaction force
GRFz$_{\text{peaks}}$	Vertical, normal peak forces (N kg^{-1}) during early and late stance relative to the force plate and body weight
GRFy$_{\text{peaks}}$	Antero-posterior (longitudinal) shear peak forces (N kg^{-1}) during early and late stance relative to the force plate and body weight
ES	Early stance, 5% to 25% of the time-normalized stance phase period
IC	Initial contact, heel-strike, the start time of the stance phase
LMF	Local muscle fatigue
MDF	Median frequency of the motor unit action potentials on electromyography data
MVC	Maximum voluntary contraction
P-value	Probability value (≤ 0.05) of observed results to be statistically significant
QTM	Qualisys track manager, software used for motion tracking
RCOF$_{\text{peak}}$	Peak required coefficient of friction during early (0% to 50%) and late (50% to 100%) stance phase
RCOF$_{\text{peakadopted}}$	Peak required coefficient of friction during early (5% to 25%) and late (75% to 95%) stance phase
RMS	Root mean square
RPE	Rating of perceived exertion (RPE) between 6 and 20 on the Borg's scale
SD	Standard deviation
SP	Stance phase, IC to FC by the dominant foot in the same step
SL	Stride length (cm), distance from ipsilateral IC point of heel to the next ipsilateral IC point during gait by the dominant foot
SDN	Stride duration (s), time between the ipsilateral and subsequent initial contacts of the dominant foot during gait
SS	Stride speed (m s^{-1}) = SL ÷ SDN
t-value	It is a ratio of the difference between the mean of the two sample sets among the population and the variation that exists within the sample sets.
LS	Late stance, 75% to 95% of the time-normalized SP period
angle$_{\text{peak}}$	Joint peak relative angle (°) during ES and LS periods relative to the incline surface
angle$_{\text{min.}}$	Joint minimum foot angle (°) during ES and LS periods relative to the incline surface
ang.$_{\text{velx.peak}}$	Angular peak velocity (° s^{-1}) during ES and LS periods
ang.$_{\text{accx.peak}}$	Angular peak acceleration (° s^{-2}) during ES and LS periods

1. Introduction

Walking downwards on a slope alters postural alignment in order to maintain equilibrium, and it involves an altered gait strategy to retain balance. For the healthy fit individuals, negotiating a moderate downward slope offers a little challenge, however, otherwise persons with musculoskeletal complaints perhaps associated with aging, overweight or moderate injury may prove challenging with an increased fall risk, when walking down an incline. It is known that walking efficiency decreases with muscle fatigue and exhaustion, as fatigue directly affects the key features of the sensorimotor system, which disorganizes voluntary control of movement and accuracy. Studies have shown that the effects of motor fatigue [1] due to repetitive activities reduce muscular force generating capacities to a minimal level leading to decrease the joint range of motion [2]. Humans often experience fatigue and become exhausted after performing laborious tasks throughout the day in many occupations including industrial and health care workers [3, 4]. Firefighters are often required climbing long stairs rapidly while performing the rescuing tasks, which are intense and exhausting due to both central and peripheral neuromuscular fatigue. The rescue related multitasks are also stressful putting them in a vulnerable mental state or imbalanced situation. A little carelessness can cause fall related accidents, especially when walking down an incline. Not only the firefighters and workers, but also the hikers who may walk for a long duration on a mountainous path, and experience exhaustion [5]. A long day exposure at work during standing or walking causes the reduction of working efficiency and force generating capacity of the anti-gravity muscles [6]. The collective effects from prolonged standing and a poor or an awkward working position cause discomfort in the lower back, legs, and feet with an increase of overall body and local muscle fatigue (LMF) at the end of a long working day.

There are inclined, slow-moving travelators available at the airports, railway stations and supermarkets. The commuters need to pass such inclined structures in daily purposes. Exhaustion at work may result in slips, stumbles due to LMF in the legs leading to fall accidents in an urgent situation when walking downhill [7]. Slip-induced fall accidents are the significant causes of fatal injuries and economic losses [8]. An approximately 10% of the deaths occurred in the workplace (especially in the developed countries like U.S.A.) were caused by falls, and the majority ($\sim$ 85%) were reported during passing different levels, such as ramps, steps, and stairs. Identifying the risk factors causing slip-induced falls is the key to develop better preventive measures to reduce fall accidents. Studies in combination with biomechanical testing suggest that poor balance due to LMF may be one of the risk factors for slip-induced falls. Walking gait biomechanics and the causes of slips and falls on various gradients [9–12], changing the slip resistance of the environment through the application of contaminants [13] were compared to horizontal, however, these studies have not taken the effect offatigue into account. Additionally, gait parameters like coefficient of friction (COF) [14] was considered to establish the relationship between the measures of floor surface slip resistance as predictors, when slip severity was compared between younger and older adults [15] too, but during level walking.

Studies of temporo-spatial and lower limb joint kinematics reported that with an increasing degree of walkway inclinations: walking speed and stride length (SL) decrease but cadence increases, when walking downwards [16, 17]; on the contrary, SL increases, and cadence decreases when walking upwards [18]. Local dynamic stability of walking is considered a sensitive measure for neuromuscular performance [19]. Most of the gait analyses after inducing fatigue was performed on level surfaces, however, one study, which reported that the number of slip cases increased when the inclination angle reached 10° or above post-fatigue [20]. In previous studies, various protocols and devices have been used, for example, sit to stand [21–23], isokinetic knee or ankle extension [24, 25], endurance walking on treadmill [26], repetitive knee movements by using a Biodex dynamometer [27] as well as a cycle ergometer [19] to induce fatigue before analyzing gait and stability.

Stair ascent is a strenuous task compared to level gait or walking on ramps and considered as an exertion in daily life [28–30]. Stair ascending demands a significantly large range of joint motion and engages every major muscle in lower body. This vertical motion challenges, particularly on the leg muscles to resist and bear the whole-body weight against gravity [31, 32]. Ascending stairs requires a higher muscular activity, as well as better balance and co-ordination to stabilizing, compared to a walk on a level surface, horizontal motion [30, 33]. A couple of recent laboratory studies have explored the stair ascending capacities until exhaustion, when people ascended the stairs on a machine at their maximum [34] and submaximum [35] speeds. These studies have reported that LMF in the legs due to highly repetitive ascending movements causes an early exhaustion, thus, constrains the endurance of stair ascent and overall physiological performance. It has been found that the LMF affects the spatial and temporal features of gait [36]. Literature also showed that prolonged and (or) repeated exposure in an unpleasant environment like cold, and fatigue induced by sustained physical exertion, or both combined can impair the gait biomechanics [5]. There might be changes in the motor pattern recruitments due to high demand and mobility just after the exhaustive ascent, that leaves a little reserve capacity [37] for the continuation of walking and may lead to unexpected events during emergency situations. Hence, it is essential in evacuation research to identify any potential risk factors altering gait patterns due to fatigue that can cause slips and fall-related accidents [38], thus affecting evacuation capacity, flow, and group dynamics.

Importantly, the pattern of fatigued walking gait dynamics either up or down a slope surface is quite undocumented, especially considering an evacuation situation with an exhaustive physical state. However, one recent study on gait biomechanics after an exhaustive stair ascent showed that leg fatigue constrained both the step and SL durations, foot, and ankle angles during initial contact (IC) of the heel and final contact (FC) of the toes while walking up a 10° inclined walkway. These constrained parameters indicated perturbed gait, and increased risk for fall accidents when walking upwards and working on the slopes [7]. This previous study indicated that further studies are required to examine the consequences of physical exhaustion due to previously ascending stairs at maximum speed, on walking down an incline. This is required for firefighting rescue tasks in an emergency. The effects of whole-body exhaustion and leg LMF on gait biomechanics and slip propensity needs to be examined and reported, while walking downwards on a gradient surface. Another previous study compared also the kinetic and kinematic patterns, for example, cadence, stance phase (SP) and gait cycle duration between stair climbing and level walking [39].

Therefore, this present study was aimed to examine the gait kinetics and kinematics of healthy younger participants' during each step (stance phase, SP) downwards on a 10° incline, immediately after the stair ascending task until exhaustion

[34]. The walking gait data was recorded in a synchronized system including electromyography (EMG), 3D motion capture, and a force plate. The specific objective of this laboratory study was to investigate the effects of post-stair ascending exhaustion on the peak of the gait ground reaction forces ($GRFs_{peak}$); required coefficient of friction ($RCOF_{peak}$); leg joints' peak angles ($angle_{peak}$), angular velocities ($ang._{velx.peak}$), angular accelerations ($ang._{accx.peak}$) while walking downwards on an inclined walkway. Moreover, the minimum angle ($angle_{min.}$) of the foot as well as the leg muscle activity in EMG amplitude (AMP) and median frequency (MDF) were also observed during the SP [7]. We hypothesized that physical exhaustion and leg muscle fatigue would shorten the SP and stride duration (SDN), SL, as well as stride speed (SS), thus adversely affect the gait pattern and parameters including $GRF_{peaks.}$, especially the normal vertical ($GRFz_{peak}$), anteroposterior or longitudinal shear ($GRFy_{peak}$), $RCOF_{peak}$, the lower limb joints' $angle_{peak}$, $angle_{min.}$, $ang._{velx.peak}$, and $ang._{accx.peak}$ during both early stance (ES) and late stance (LS) phases.

2. Materials and Methods

2.1. Subjects

A total of eighteen, equal numbers of men and women, healthy, and physically active university students agreed to take part in this study. The participants had no history of any kind of musculoskeletal, neurological, or cardiovascular complaints and disorders. To determine inclusion, the test subjects completed a health declaration questionnaire that covered basic information on their medical history, disabilities, and medications. A written consent was also obtained from each participant. This lab-based study in a controlled condition focussed only on the main study variables and tried to limit other confounding variables including the effect of individual differences. The anthropometric data of the participants was tested for normality. All of these were found normally distributed. The means of anthropometric and physical fitness data of the study participants with standard deviations (SDs) in parentheses and ranges are given in Table 1.

The subjects received both verbal and written information about the test procedures twice: on the first occasion during the recruiting period and once again just prior to the tests. The methods and procedures used in this study comply with the

Table 1
The Means (SDs), and Ranges of the Participants' Anthropometric Data

	Age (years)	Weight (kg)	Height (m)	BMI ($kg\ m^{-2}$)	BSA_{du} (m^{-2})	$\dot{V}O_{2max}$ ($mL\ min^{-1}\ kg^{1}$)	HR_{max} ($b\ min^{1}$)
Mean (SD)	26.7 (4.0)	68.0 (11.3)	1.73 (0.11)	22.7 (2.0)	1.8 (0.2)	48.5 (5.4)	192.0 (8.8)
Range	18.0–32.0	51.0–85.7	1.56–1.94	27.3–19.2	1.50–2.09	38.1–55.7	176–212

BSA_{du} body surface area was calculated following *Du Bois* formula (BSA = 0.007184 × weight 0.425 × height) ethical principles provided by the World Medical Association [40]. The Regional Ethical Review Authority in Lund, Sweden also approved the study protocol (Dnr. 2016/1061). The subjects were ensured that they could terminate the test at any time without providing any reason.

2.2. Data Collection Procedure and Equipment

The participants were provided with standardized individual sports clothing and shoes to which reflecting markers and electrodes were attached during the ascent on a stair machine and walking tests. The entire experiment was conducted during two separate visits. The subjects were asked to refrain from drinking alcohol, regular sports, and strenuous exercises for at least 24 h before each visit. They were also requested not to have a heavy meal or drink coffee or tea for at least 2 h before the visits. At the start of each visit, the subjects were able to acquaint themselves with the treadmill and stair machine during the visit number 1 and 2, respectively. After confirming participation, on the first visit, the subject's maximal aerobic capacity ($\dot{V}O_{2max}$) test was carried out on a treadmill (Exercise™, x-track elite, Sweden) using a maximal graded exercise testing (GXT) protocol [34]. The obtained $\dot{V}O_{2max}$ value of each participant using GXT method was used to determine the individual's maximum ascending step rates corresponding to the subject's 100% $\dot{V}O_{2max}$.

These individualized step rates were used later during the second visit, when the subjects climbed on a stair machine to induce whole-body exhaustion and leg muscles fatigue. This second visit took place at least 24 h to 48 h after the first visit. Synchronized measurements were conducted to collect the subjects' gait SP duration, kinetics, ground reaction forces (GRFs), coefficient of friction (COF), leg joints' kinematics and muscles' EMG activity while walking down a 10° inclined stationary walkway. These data were recorded both before and after an exhaustive stair ascent, which was performed on a stair machine [34]. The subjects were encouraged verbally to continue climbing as long as possible; however, they were allowed to quit any time when they wanted and could not climb anymore. On both visits, fingertip blood samples were also obtained using a hand-held analyzer Lactate Scout + (EKF Diagnostics, Penarth, Cardiff, UK) to measure the lactate levels in the blood (BLa^-) immediately after the exhaustive running on a treadmill for $\dot{V}O_{2max}$ test, and stair climbing to ascertain the exhaustion and fatigue. An accumulation of BLa^- in the body is an indicator of metabolic alterations during high intensity to maximal exercise, and it is being used as a reliable marker to quantify the exercise intensity. The accumulation of BLa^- is varied between the individual's fitness and tolerance. A post-exercise BLa^- value of ≥ 8 mmol l^{-1} to 10 mmol l^{-1} is commonly used as a threshold for reaching a maximum exercise intensity. The subjects also rated perceived exertion (RPE) between 6 and 20 on the Borg's scale. A RPE value of ≥ 17 to 18 is traditionally used as a $\dot{V}O_{2max}$ criterion for comparison to confirm fatigue, and maximum exhaustion [41]. Both BLa^- and RPE values are widely used as secondary criterion of $\dot{V}O_{2max}$ test.

2.2.1. EMG and Muscles The EMG biomonitor, Megawin (ME6000-T16 Mega Electronics, Kuopio, Finland), was synchronized with the motion capture system, Qualisys Track Manager (QTM), with software version 2.17. To observe walking muscle activity changes pre- and post-exhaustion, we chose to observe the following four lower limb antigravity muscles: vastus lateralis (VL), a knee extensor; rectus femoris (RF), both a hip flexor and knee extensor; gastrocnemius lateralis (GL), a foot plantar flexor and knee flexor; and tibialis anterior (TA), a prime mover for ankle dorsiflexion. The EMG electrodes was placed on the dry, hairless, and oil-free skin. Prior to applying the electrodes and better adhesion, the hairy skin was only shaved, later cleaned with alcohol prep pads to make it oil-free and abraded lightly with fine sandpaper. Pre-gelled bipolar (AgCl) surface electrodes (Ambu Neuroline-720, Ballerup, Denmark) were placed along the direction of the underlying muscle fibres with a center-to-center distance of approximately 10 mm to 20 mm [42]. The reference electrodes were attached to the bony tubercle and shaft of the tibia, and fibular head. The same investigator performed the placement of the electrodes on all subjects and followed the recommendations of the SENIAM project (Surface Electromyography for the Non-Invasive Assessment of Muscles) (www.seniam.org, Enschede, Netherlands).

2.2.2. Maximum Voluntary Contractions (MVC) The raw EMG of the three isometric maximum voluntary contractions (MVCs) of the dominant leg knee extensor (VL), hip flexor (RF), ankle plantar (GL) and dorsiflexor (TA) were ascertained just prior to the stair-ascending test. The mean of the peak root mean square (RMS) of the maximum EMG muscle activity amplitude (AMP) of those obtained three MVCs was used to normalize the EMG AMPs from the stance phase (SP) of the subsequent walking trials. One of the investigators, who was an experienced physiotherapist, chose and ensured a comfortable starting position. A secured non-elastic band was fastened at a stable part of the bed or the walkway railings according to the suitable position and placement of the body to apply the maximal isometric resistance in midrange of each joint's full motion during each target muscle's contraction under strong verbal encouragement. The band was placed at the anterior part of the lower leg for VL; lower part of the thigh in bended knee for RF; plantar and dorsal surface of the forefoot for GL and TA muscles, respectively, to record the MVC of the respective muscle. Each MVC duration lasted for 3 s to 5 s with a development of the contraction for about 1 s to 2 s for the RF, GL, and TA muscles for the respective movements and directions, when laying supine on a plinth, except the VL, which was obtained in sitting position [34].

2.2.3. Walking Tests The walking downwards trials were conducted on a linear, 10° inclined dry stationary walkway. The surface of the walkway was made of plain metal plate. The total length of the walkway with an added extension was 7.35 m and the width was 1.0 m [43]. The walkway had a built-in force plate with a 60 × 40 cm surface area on the top (Kistler 9281B, Switzerland). It was synchronized with the QTM to record the three-dimensional GRFs and leg muscles EMG activities. The center of the force plate was located at 3.23 m from the

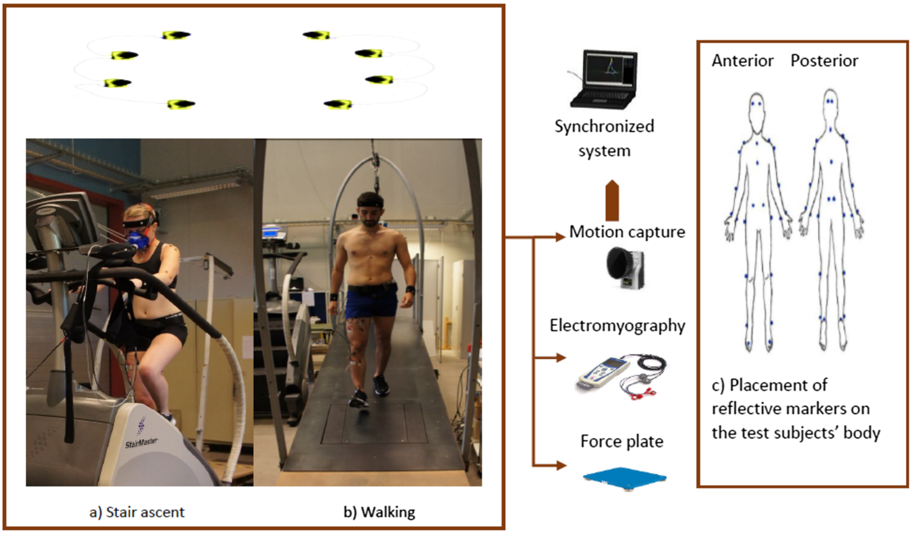


Figure 1. Experimental setup: (a) stair machine with a subject ascending until exhaustion, (b) subject walking down a 10° inclined walkway, and (c) placement of the reflective markers for motion capture.

lower end of the inclined walkway. The data acquisition (DAQ) System 5695A1 with a 9865A type amplifier was connected to the force plate. Motion cameras were calibrated with an L-shaped bar, which was aligned with the force plate in the right walking direction and coordinate system of the force plate. The location and inclined position of the force plate was identified by making a short (1 s) recording in the QTM, while four markers were placed on the four corners of the force plate. All four markers were then identified by coding them following the instructions and guidelines of the equipment manual.

The subjects wore the same model (Nike Air Relentless 6, Vietnam) sports shoes. Before the walking trials, the subjects were asked to walk up and down to make themselves familiarize with the walkway (see Figure 1). The subjects spent a reasonable amount of time as per instruction to find a self-preferred pace and walk as naturally as possible with the conditions so that the dominant foot strike on the force plate to get the GRFs. They were instructed to look only forward, and avoid focussing on the force plate while walking.

2.2.4. Markers for Gait Motion Capture After the MVC tests, thirty-two (12 mm diameter) reflective passive markers were attached bilaterally to the subjects' body part, apart from the axial markers, which were placed on the top of the sternum, bottom of the xiphoid process, on the spinous process of cervical 7 (C7) and thoracic 10 (T10) (see Figure 1c). The motion of the markers was tracked using the QTM's eight-camera Pro-Reflex motion capture system (Qualisys AB, Gothenburg, Sweden). With the electrodes and markers in place, the subjects first per-

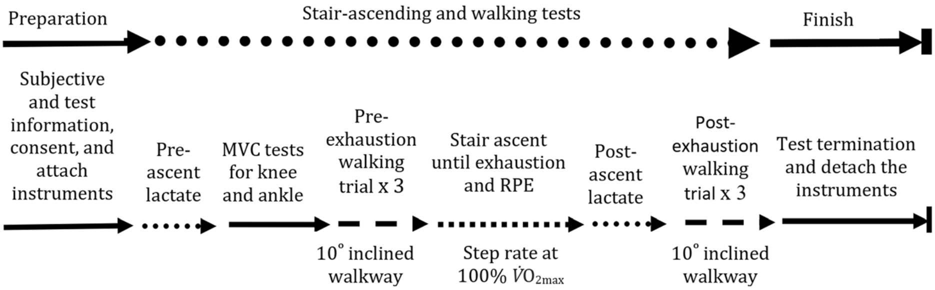


Figure 2. Schematic flowchart and the protocol of the walking trials on a 10° inclined walkway before and after stair ascending until exhaustion.

formed static standing calibration trials in a neutral position landmark to aid subsequent marker identification. Then, the subjects did the first three pre-exhaustion walking trials both upward and downward directions on the inclined walkway. Following the pre-exhaustion walking trails, the stair ascent was performed on the stair machine to induce whole-body exhaustion and local muscle fatigue (LMF) in the legs [34]. The final three post-exhaustion walking trials were started immediately after the participants stopped their stair ascents within $\sim$ 30 s, while the blood sample was taken from the participant's fingertip for measuring the BLa^- and they rated their subjective exertion level on the Borg's scale. If this procedure for the completion of the recordings of post-exhaustion walking trials was prolonged for more than 1 min to 2 min, the participants were asked to repeat the stair ascent to re-induce leg fatigue and exhaustion. A flow chart of the walking-test procedure during the second visit is presented in Figure 2.

2.3. Data Processing

In this present study, the following data analysis procedure was used to observe the differences in biomechanical changes between pre- and post-exhaustion gait trials. The entire stance phase (SP) duration of individual's each gait trial was identified relative to the vertical ground reaction force (GRFs) and the time was normalized with 0% being the initial contact (IC) of the heel and 100% being the final contact (FC) of the toes of the dominant foot. Then, the total SP duration was bisected into the mid-point (50%) to get two sub-phases, namely, early stance (ES) and late stance (LS). These two sub-SPs, ES and LS were further subdivided into the periods between 5 and 25%, and between 75 and 95% of the SP duration, respectively, to calculate the required coefficient of friction (RCOF) during IC and FC phases on the walking surface. The methods including the details of these procedures for calculating leg muscle's electromyography (ÈMG), gait kinetic and kinematic variables have been described in the different sections below and in previous study by Halder et al. (2021) [7].

2.3.1. Muscle Electromyography (EMG) Signal Processing and Normalization The EMG sampling rate was set at 1024 Hz. The EMG data was also time normalized to 100% of the total stance phase (SP) duration, when 0% is representing the IC and 100% is the FC of the dominant foot. The raw EMG signals (Figure 3) were first filtered with a band-pass between 20 and 500 Hz using the Butterworth function in MATLAB. Low end cut-off removes electrical noise associated with wire sway and movement artifacts, while the high-end cut-off eliminates higher frequency noise and signals from various sources at the skin–electrode interface [44] during this dynamic task. The time normalized EMG data points were then RMS averaged, and these data points or each muscle were normalized by the mean of maximum AMP value of the three MVC trials of the respective muscle. The normalized RMS AMP (Figure 4), and median frequency (MDF) (Figure 5) of the leg muscles' EMG activity values of the entire SP are shown in the charts in the results section. The MDF was calculated by using Fast Fourier Transform (FFT) from the frequency spectrum analysis. The EMG power spectral density was computed via Welch's averaged modified periodogram, with 1024 sample analysis windows, overlapping by 50% [45].

The averages of the normalized RMS AMPs in %MVC, and MDFs in Hz of the three pre- exhaustion walking trials were calculated to yield an average curve for each subject. The same procedure was applied to the post-exhaustive trials. The mean AMP (Figs. 4a-d) and MDF (Figs. 5a-d) figures for all (18) subjects were plotted for each muscle both pre-and post-exhaustion walking trials. The mean and standard deviation (SD) of EMG AMP and MDF were calculated for each of the sub-SPs for all subjects (Table 2).

2.3.2. Kinetic and Kinematic Data Normalization and Processing Three ground reaction forces (GRFs) from the force plate, namely, the normal, which is vertical ground reaction force (GRFz), antero-posterior shear force (GRFy), and lateral shear force (GRFx), were obtained using an eight-channel amplifier. The GRFs data were sampled at 1000 Hz. GRF data was time normalized similarly to the EMG data for the whole SP (0% to 100%) duration, when 0% is the IC during the ES and 100% is FC in the LS phase [7, 46]. The onset of the individual gait step for the SP period was defined using the raw GRF data, when GRFz reached 10 newtons (N) during the IC of the heel, and the end was determined when the GRFz dropped below 10 N during the FC of the foot at LS phase. 10 N was set as a standard threshold to identify the SP duration. Subsequently, the force data were filtered using a fourth-order Butterworth low pass filter (60 Hz cut-off frequency) and normalized to the participant's body weight (N kg^{-1}). Moreover, SL and its duration (SDN) were retrieved between ipsilateral IC and subsequent IC of the dominant foot on the force plate traced by the 3D trajectories of the foot movement.

Kinematic data were sampled and recorded at 200 Hz in the QTM. Motion capture files were processed in the QTM, including labelling and correction of marker data. One walking model for each subject was developed after identification of the trajectories and form links between markers, which was then applied to the respective trials under Automatic Identification of Markers (AIM) model in the QTM program. Missing segments of marker data smaller than 10 frames (5 ms) were algorithmically reconstructed using the QTM's default method of polynomial gap filling. The remaining gaps, about 5% to 10%, were filled using the best option of the techniques provided by the QTM program, either linear or polynomial on a case-by-case basis. Additionally, the joint angles, angular velocities, and accelerations were time-normalized to the SP duration.

2.4. Calculation and Statistics

All the parameters and related figures were calculated and reported within the entire stance phase (SP) duration from 0 to 100% for the dominant foot. All the parameters were divided into two sub-phases within the SP duration: ES and LS, depending on the vertical GRF (GRFz). The method was presented early in the paper by Halder et al. (2021) [7]. The GRFz are normally characterized by two peaks within the SP, the first one appears shortly after IC during ES phase, and other one comes just before the FC, during LS phase. These $\text{GRFz}_{\text{peaks}}$ represent the maximum vertical GRF values during both ES and LS phases. A trough separates these two $\text{GRFz}_{\text{peaks}}$ (Figure 3a). The lowest value of the trough was identified by using MATLAB's' built-in find peaks function to separate the SP into the two sub-phases. A threshold value of 50 N was used to eliminate the small peaks arising due to noise in the data. The threshold ensures that the force on either side of the peak drops off by at least 50 N. This was used to identify $\text{GRFz}_{\text{peaks}}$ for both during ES and LS phases, respectively. IC starts when GRFz is above 10 N as threshold and ends with FC when the force is below 10 N. The peaks of the negated signal were also found using the same method and were used to identify the midpoint of the SP separating ES from LS. Moreover, the two peaks for both vertical ($\text{GRFz}_{\text{peaks}}$) and antero-posterior shear ($\text{GRFy}_{\text{peaks}}$) were obtained from both whole ES (0% to 50%)§ and whole LS (50% to 100%)§ time normalized periods of the SP, as expressed: whole_$\text{GRFz}_{\text{peaks}}{}^{\S}$ and whole_$\text{GRFy}_{\text{peaks}}{}^{\S}$.

To find the critical point out for slip related fall risks, the required coefficient of friction (RCOF) was calculated for each walking trial and for both sub-SPs, by dividing the antero-posterior force (GRFy) by the vertical force (GRFz): (GRFy/GRFz) [20]. The third absolute peak of the coefficient of friction (COF) is considered as the required coefficient of friction ($\text{RCOF}_{\text{peak}}$) during the IC to avoid slips and fall incidents. The method used for finding the $\text{RCOF}_{\text{peak}}$ was suggested by Chang et al. (2012) [47]. The aim was to evaluate the relationship between the mean EMG and the RCOF values within the same period. $\text{RCOF}_{\text{peaks}}$ were retrieved during the whole ES (0% to 50%)§ and whole LS (50% to 100%)§ phase of the time-normalized period. Moreover, in this study, a combined method was also adopted based on the literature, to determine the $\text{RCOF}_{\text{peak}}$ [47–49] from a specific period of the ES and LS phases, referred as $\text{RCOF}_{\text{peak adopted}}$ Specifically, this $\text{RCOF}_{\text{peak adopted}}$ during ES was retrieved between 5 and 25% of the time-normalized periods at the time point of $\text{GRFz}_{\text{peak}}$. This method is based on the method recommended by Chang et al. (2012), to get the 3rd peak (Figure 3b), and the $\text{RCOF}_{\text{peak adopted}}$ during LS phase was retrieved between the 75% and 95% of the SP period [47].

Both the $\mathrm{GRFz}_{\mathrm{peaks}}$ and $\mathrm{GRFy}_{\mathrm{peaks}}$ were retrieved in the equivalent period as for $\mathrm{RCOF}_{\mathrm{peak\ adopted}}$ i.e., from ES (5% to 25%), and LS (75% to 95%) time normalized periods of the SP. Similarly, the peak angles ($\mathrm{angle}_{\mathrm{peak}}$), velocities ($\mathrm{ang.}_{\mathrm{velx.peak}}$), and accelerations ($\mathrm{ang.}_{\mathrm{accx.peak}}$) for the hip, knee, ankle and foot joints were also determined from the kinematics motion data and for the same synchronized time periods of the $\mathrm{RCOF}_{\mathrm{peak\ adopted}}$ calculation time window during both ES (5% to 25%) and LS (75% to 95%). Additionally, the minimum angle ($\mathrm{angle}_{\mathrm{min.}}$) was calculated to get to know the foot position relative to the inclined surface on the force plate [50]. These variables were obtained by following the methods of mechanical analysis of human motion [51]. The mean EMG AMP and MDF were also calculated following the same $\mathrm{RCOF}_{\mathrm{peak\ adopted.}}$ calculation time window.

The joint's relative angle was calculated relative to the 10° inclined surface during the SP. The angle is formed between two adjacent segments, presented as the angle formed at the articulation. In all cases except foot, the positive joint angle values represent flexion and dorsiflexion ($> 0°$), while the negative joint angle values represent extension and plantarflexion ($< 0°$). Foot angle was also calculated as 0° as a neutral angle relative to the 10° inclined surface, when a person stands still. The projection of three marker positions on to the sagittal plane were used to calculate each angle of the leg's major joints for the whole SP duration; for the hip: T10 spinous process, greater trochanter of femur, lateral knee; for the knee: greater trochanter of femur, lateral knee, lateral malleolus of fibula; for the ankle: lateral knee, lateral malleolus of fibula, base of 2^{nd} toe; and for the foot relative: lateral malleolus of fibula, base of 2^{nd} toe relative to the surface.

To calculate the angular velocity and acceleration over time, a spline was fitted to the angular values and used to find the first and second derivatives. The spline was fitted using the MATLAB function 'smoothingspline', with the 'smoothingparam' value set to 0.9999. The "goodness-of-fit (gof)" output from the fitting operation was used to check the fit. The ´smoothingparam' value affects how closely the spline follows the data points, with a value of one indicating a perfect fit, that is, no smoothing. The ´smoothingparam' value was selected as a compromise between the following angular values exactly and the level of noise in the calculated first and second derivatives. The first and second derivatives of the fitted spline were calculated using the MATLAB function 'differentiate'. Moreover, the SL and duration (SDN) from each gait trial were retrieved in the QTM. The 'distance travelled' function was used to trace the heel marker in a few cases, however, when that was not traceable, then either the marker on the ankle or the 2^{nd} toe was used between the successive ICs of the dominant foot (heel), and later, the calculation was made by using the 'magnitude' function.

. The mean and standard deviation (SD) values were calculated for SP duration, SL, SDN, SS, $\mathrm{RCOF}_{\mathrm{peak}}$, $\mathrm{GRFz}_{\mathrm{peak.}}$, $\mathrm{GRFy}_{\mathrm{peak.}}$, $\mathrm{angle}_{\mathrm{peak.}}$, $\mathrm{angle}_{\mathrm{min.}}$, $\mathrm{ang.}_{\mathrm{velx.peak.}}$, $\mathrm{ang.}_{\mathrm{accx.peak.}}$, EMG AMP, and MDF from the three SPs (both ES and LS phases). The SPs were obtained from three different walking trials on the force plate for each subject, and then for total 18 participants in each occasion on both before and after exhaustion [52]. The normal distribution of the gait biomechanics and participants' anthropometric data were assessed using the Shapiro–Wilk test with a significant (Sig.) value of ≥ 0.05 to be considered normally distributed. Differences between pre-and post-exhaustion gait kinetics and kinematics dataset (108 trials in total) for all dependent variables were assessed using two-tailed paired t-Student test [53, 54]. A probability (p) value of ≤ 0.05 was considered to be statistically significant. The calculations and statistical analyses were carried out in MATLAB *R2016a* (The MathWorks Inc., Natick, MA, U.S.A.), *Excel 2016* (Microsoft Corporation, U.S.A.) and *Statistical Package for the Social Science* (SPSS), version 24.0 (IBM Corporation, U.S.A.).

3. Results and Discussion

This study reports the effects of whole-body exhaustion on:

- gait stance phase (SP), stride length (SL) and stride duration (SDN)
- ground reaction forces ($\mathrm{GRFs}_{\mathrm{peak}}$)
- required coefficient of friction ($\mathrm{RCOF}_{\mathrm{peak}}$)
- joint angle peak ($\mathrm{angle}_{\mathrm{peak}}$) and angle minimum ($\mathrm{angle}_{\mathrm{min.}}$)
- angular velocity peak ($\mathrm{ang.}_{\mathrm{velx.peak}}$)
- acceleration peak ($\mathrm{ang.}_{\mathrm{accx.peak}}$) and
- major leg muscles electromyography (EMG) amplitudes (AMPs) and median frequencies (MDFs)

These measurements were carried out in the stance phase (SP) during the early (ES) and late stance (LS) periods of walking down a 10° inclined surface. The main and significant findings of the study were the decreased SL, the peak vertical force ($\mathrm{GRFz}_{\mathrm{peak}}$) with an increased antero-posterior force ($\mathrm{GRFy}_{\mathrm{peak}}$), and required coefficient of friction ($\mathrm{RCOF}_{\mathrm{peak}}$), when the subjects walked down a 10° inclined surface after the exhaustive stair ascent.

3.1. EMG AMP and MDF during exhaustive gait down an incline

Physical exhaustion of the subjects was evidenced by the high mean BLa^{-} value of 14.4 mmol l^{-1} at the end of their stair ascents at maximum speed. The exhausted ascending task on the stair machine was terminated by the subjects themselves due to high strain on both the cardiovascular system and leg muscles, when a very high mean RPE level was also observed 18.2 on the Borg's scale. The end durational stair ascent EMG results evidenced the onset of leg's local muscle fatigue (LMF) in that previous study by Halder et al., (2020) [34]. In this gait analysis of walking downwards, none of the muscles' mean EMG amplitudes (AMPs) during 5% to 25% (ES) and 75% to 95% (LS) periods were significantly changed between the pre-exhaustion and post-exhaustion trials, except the tibialis anterior (TA) muscle. The EMG AMP of TA was increased significantly, $t(17) = 2.19$, $p < 0.042$, during LS phase (Table 1, Figure 4), while the other measured muscle's EMG AMPs have shown an increasing pattern. Similarly, none of the median frequencies (MDFs) of the measured muscles were significantly decreased when walking downwards due to fatigue. But the mean EMG MDF values were found to be lower during the post-exhaustive walking trials than the pre-exhaustion (Table 2, Figure 5). The results including the shift of EMG MDFs towards lower values [55, 56], significantly increased EMG AMPs of TA muscle during post-exhaustion downwards walking at LS phase, and increasing pattern of the AMPs of other measured muscles are consistent with the evidence of the onset of leg's LMF due to ascending stairs until exhaustion [35]. Usually, an increase in EMG AMP and a decrease in MDF of muscle activity indicate muscle fatigue [57, 58]. The post-exhaustion LMF on the major leg and thigh muscles were also observed in the previous study, when the subjects walked upwards after the end of the same stair ascents on a machine [7].

Examples of pre-exhaustion raw muscle activity in microvolts (μV) recorded from the EMG measurements of four leg muscles walking down (one trial) a 10° incline are presented in Figure 3.

Although, there were no significant differences observed in the mean EMG MDF results of any of the measured muscles between pre- and post-exhaustion walking trials, the mean MDF values of the VL, RF and TA muscles were found towards the lower end during ES, post-exhaustive walking trials than pre-exhaus-

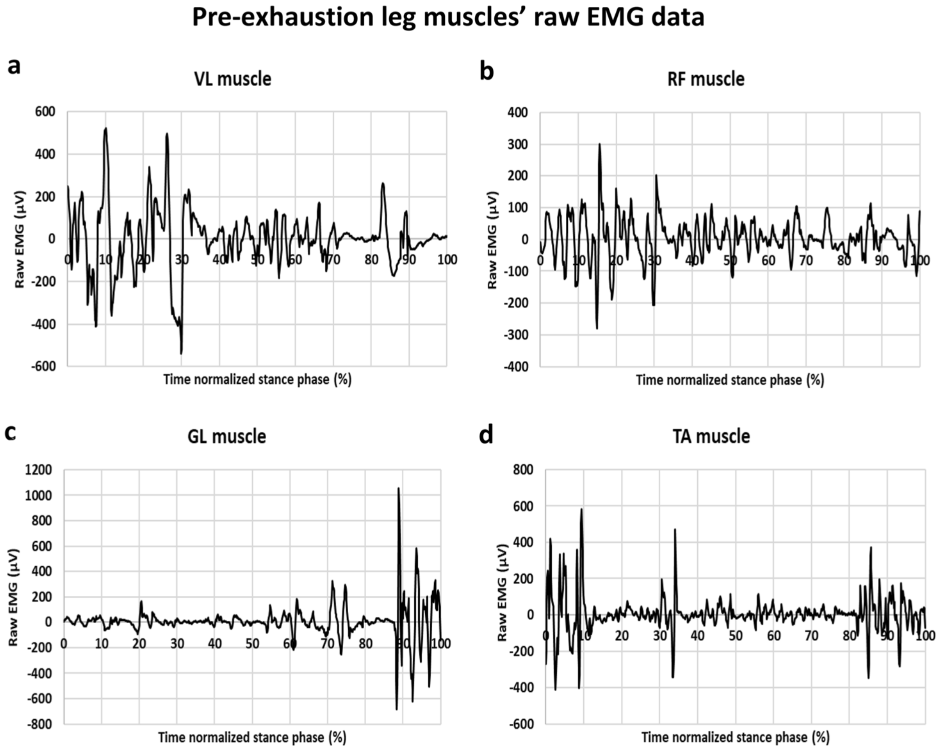


Figure 3. The raw EMG of VL (a), RF (b), TA (c), and GL (d) muscles during time-normalized stance phase (SP) 0%, initial contact (IC) to 100%, final contact (FC) when walking down a 10° inclined walkway.

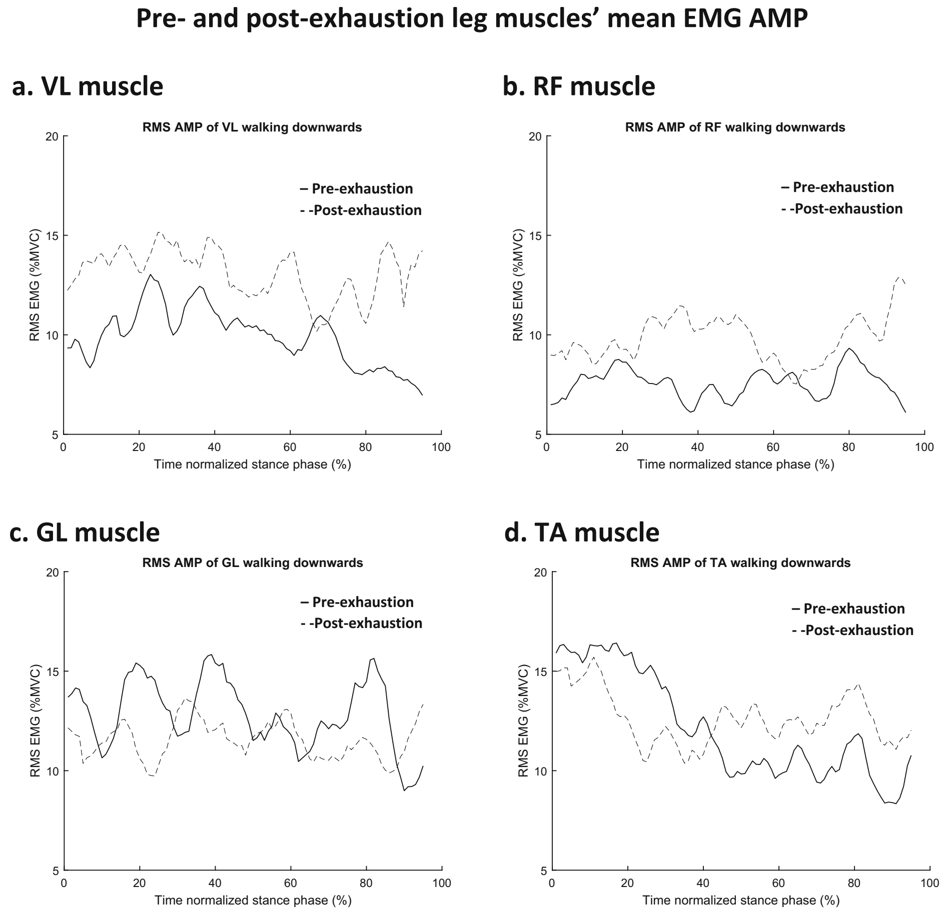


Figure 4. The mean EMG AMPs of VL (a), RF (b), TA (c), and GL (d) muscles during time-normalized stance phase (SP) 0%, initial contact (IC) to 100%, final contact (FC) pre (solid lines) and post-exhaustion (dashed lines) when walking down a 10° inclined walkway.

tion (Table 2, Figure 5). These results might be due to the fact that the muscular ability did not require so much effort while walking down an incline, as it seemed, a comparative high effort was necessary during post-exhaustion walking in an upward direction [7].

Additionally, the calculation window for the EMG was too short (only one step on the force plate) to allow the detection of differences, but these two short subphases, ES (5% to 25%) and LS (75% to 95%) divided in this study were necessary for the synchronized analysis and comparison with other kinetic and kinematic data. The data were only collected at uncontrolled walking speeds by the healthy participants; therefore, the mean EMG profiles (Figs. 4 and 5) vary some-

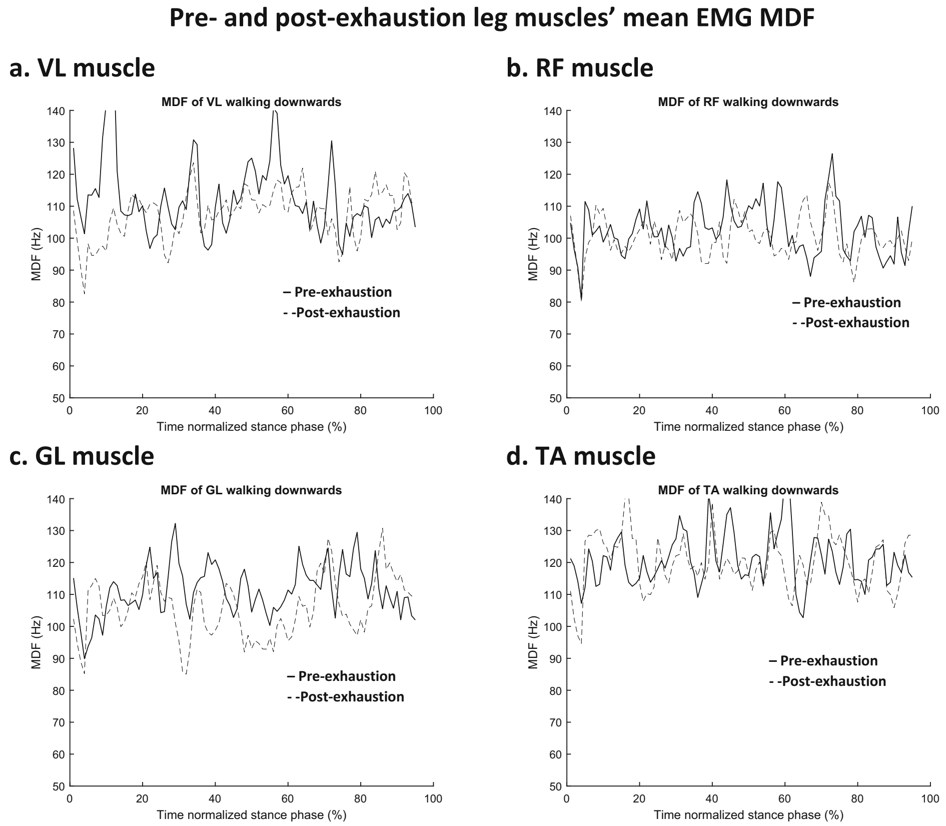


Figure 5. The mean EMG MDFs of VL (a), RF (b), TA (c), and GL (d) muscles during time-normalized stance phase (SP) 0%, initial contact (IC) to 100%, final contact (FC) pre- (solid lines) and post-exhaustion (dashed lines) when walking down a 10° inclined walkway.

what compared to the standard profiles. It is recognized that raw EMG (Figure 3) profiles can change markedly with speed [59].

It should be noted that a large variation in SDs was observed in the mean results in this group of participants. These variations are mainly due to individual anthropometric differences, for example, muscular cross-sectional areas, sizes, lengths, strengths, walking patterns, as well as the execution of the MVCs, which were used to normalize the raw EMG data.

Only the post-exhaustive EMG AMP of the tibialis anterior (TA) muscle characterized a fatigued muscular activity with significantly higher AMPs, however the VL and RF muscles had a non-significantly higher AMPs during both ES and LS phases (Table 2, Figure 4a and b). TA muscle is important in stabilizing the ankle joint during the initial IC (heel) to absorb the foot surface contact. This is the critical phase, for slipping forward during IC period [60]. It is also the prime

Table 2
The Means with Standard Deviations (SDs) Values in Parentheses of the Electromyography (EMG) Amplitudes (AMPs) and Median Frequencies (MDFs) of Four Leg Muscles During Early Stance (ES) and Late Stance (LS) Gait Phases Between Pre-and Post-exhaustion (N = 18)

	Pre-exhaustion		Post-exhaustion	
Parameters	Early stance (ES)	Late stance (LS)	Early stance (ES)	Late stance (LS)
VL AMP (%MVC)	11.35 (10.15)	7.80 (7.18)	14.92 (12.13)	12.03 (10.38)
VL MDF (Hz)	77.34 (39.33)	70.03 (31.37)	70.85 (22.53)	90.07 (31.37)
RF AMP (%MVC)	8.30 (7.52)	7.24 (6.99)	10.23 (6.77)	11.04 (9.60)
RF MDF (Hz)	67.67 (31.59)	63.15 (16.32)	63.61 (17.81)	64.05 (17.33)
GL AMP (%MVC)	14.10 (11.26)	12.14 (10.19)	11.82 (8.66)	12.71 (8.60)
GL MDF (Hz)	78.07 (31.98)	68.74 (24.35)	70.14 (21.50)	73.70 (29.62)
TA AMP (%MVC)	17.23 (13.74)	11.34 (5.40)*	11.82 (8.66)	14.73 (7.25)*
TA MDF (Hz)	93.23 (24.44)	87.55 (31.45)	90.57 (21.85)	87.49 (19.47)

The means (SDs) values were given during ES (5% to 25%) and LS (75% to 95%) periods equivalent to average RCOF during 5% to 25% and 75% to 95% of stance phase (SP), which are critical for slipping events

*$p \leq 0.05$

mover for dorsiflexion of the ankle joint enabling the foot to clear the ground, thus crucial to avoid stumbling or tripping at LS and early swing phase before returning to slight plantarflexion after the IC [61] (Table 2, Figures 4c and 5c). Inadequate ground clearance at the FC of the LS phase to the next step due to fatigue may increase the chance of a falling incident during any emergency. Previous studies have shown that knee extensor and hip flexor muscles also decline the proprioceptive function due to fatigue from prolonged standing, heavy and repetitive activities at work, which are associated with balance decrease; this may be one of the risk factors for slip-induced falls [62, 63].

3.2. *GRFs and RCOF during exhaustive gait down an incline*

During the SP phase, over the period from IC of the heel to FC of the toes, there are mainly the normal (vertical) ($GRFz_{peaks}$) and antero-posterior shear (GRFy-peaks) components (Figure 6a) of the GRFs and their interactions between the shoe and floor surfaces are the most critical biomechanical parameters considering slips and falls. The first GRFzpeak occurs at the end of the loading phase (about 25% into SP) as full body weight is transferred to the supporting foot, while the second $GRFz_{peak}$ occurs later in the SP, but just prior to the LS phase. The $GRFy_{peaks}$ exhibits a biphasic nature indicating the walking direction related to the reaction force created by the foot placement on the force plate. The first half of the $GRFy_{peak}$ is comparatively large within the SP reflecting the forward direction movement according to the foot loading dynamics during the ES phase with greater IC of the heel. The second half of the $GRFy_{peak}$ is smaller than the first one. It occurs when the toes take off

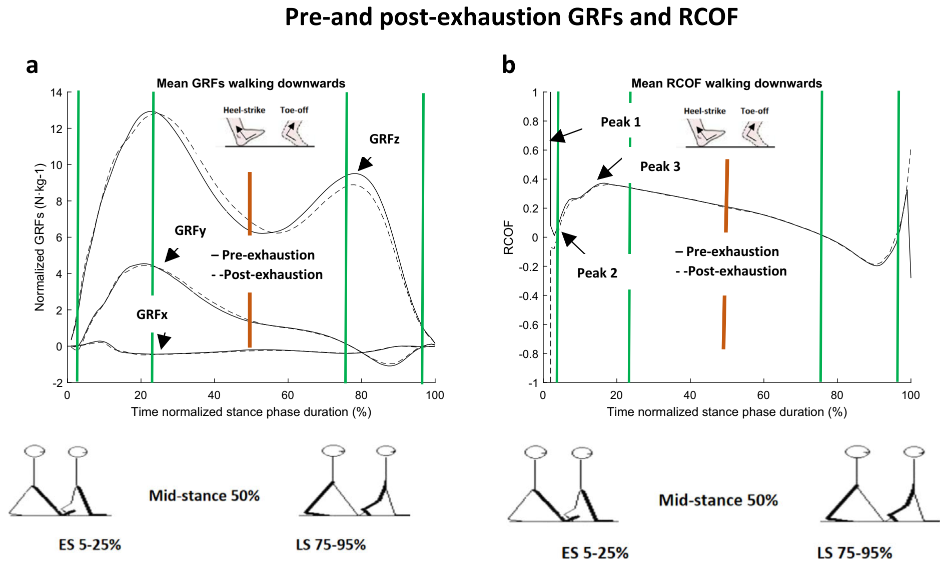


Figure 6. The mean gait ground reaction forces (GRFs) (a): vertical (GRFz), antero-posterior shear (GRFy), and lateral shear (GRFx), and required coefficient friction (RCOF) (b) = GRFy/GRFz during time-normalized stance phase (SP) 0%, initial contact (IC) to 100%, final contact (FC) pre- (solid lines) and post-exhaustion (dashed lines) when walking down a 10° inclined walkway.

and push mildly in rearward direction against the inclined surface during the FC in the LS phase [12, 20, 64] (Figure 6a and Table 3).

Moreover, the gait characteristics and frictional requirements were measured by using GRFz and GRFy forces, to maintain balance and finding differences between walking up and down an incline. Walking down an incline is much riskier for the occurrences of slipping events than walking up. During walking downward, the very first step, especially the first peak in shear GRFy (about 20% into SP after IC) is higher and being considered to be the critical phase resulting in slips and falls on a descending surface [12, 64, 65]. A slip is predictable, if the shear GRFy generated during a downward step particularly after whole-body exhaustion and leg fatigue, exceeds the available coefficient of friction (COF) between shoes and floor surface.

One of the significant findings of the effects of exhaustion and leg LMF was the reduction of normal vertical force ($\mathrm{GRFz}_{\mathrm{peak}}$) (0.64 $\mathrm{N\,kg}^{-1}$) force during LS, post-exhaustive walking trials. The mean antero-posterior shear (whole_-$\mathrm{GRFy}_{\mathrm{peak}}{}^{\S}$) force also during LS was found significantly higher (0.54 $\mathrm{N\,kg}^{-1}$) than pre-exhaustive walking down a 10° inclined walkway. The reduced post-exhaustive $\mathrm{GRFz}_{\mathrm{peak}}$ walking during LS indicates the reduction of muscle power, thus coordination during both deceleration, IC, and acceleration, FC phases. One possible explanation is that the post-exhaustive uncontrolled and restrained foot-

Table 3
The Means with Standard Deviations (SDs) in Parentheses are Presented of the Parameters

1. Stance phase	Pre-exhaustion		Post-exhaustion	
SP duration (s)	0.656 (0.059)		0.647 (0.063)	
SDN (s)	1.06 (0.08)		1.03 (0.08)	
SL (cm)	163.38 (17.52)*		155.52 (13.55)*	
SS (m s^{-1})	1.55 (0.17)		1.53 (0.21)	
2. Sub-stance phase	Early stance (ES)	Late stance (LS)	Early stance (ES)	Late stance (LS)
Whole_GRFz$_{\text{peak}}^{\S}$ (N kg^{-1})	13.26 (1.18)	10.25 (0.98)	13.18 (1.64)	10.69 (1.84)
Whole_GRFy$_{\text{peak}}^{\S}$ (N kg^{-1})	4.73 (0.64)	1.63 (0.99)*	4.69 (0.97)	2.27 (1.63)*
RCOF$_{\text{peak}}$ §	0.342 (0.031)	0.033 (0.096)*	0.322 (0.072)	0.100 (0.144)*
GRFz$_{\text{peak}}$ (N·kg^{-1})	12.73 (1.66)	9.72 (0.84)**	12.72 (1.49)	9.08 (0.85)**
GRFy$_{\text{peak}}$ (N kg^{-1})	4.64 (0.75)	0.54 (0.34)	4.67 (0.97)	0.57 (0.36)
RCOF$_{\text{peak adopted}}$ #	0.362 (0.296)	0.358 (0.055)	0.209 (0.212)	0.345 (0.135)
Foot relative angle$_{\text{min}}$ (°)	– 2.82 (5.76)	– 16.71 (6.03)	– 5.62 (7.65)	– 11.02 (14.91)
Foot relative angle$_{\text{peak}}$ (°)	19.67 (6.33)	– 9.59 (4.93)	15.34 (11.69)	– 5.03 (15.18)
Foot relative ang$_{\cdot\text{velx.peak}}$ (° s^{-1})	99.97 (41.58)	29.78 (19.81)	90.62 (50.47)	38.51 (55.89)
Foot relative ang$_{\cdot\text{accx.peak}}$ (° s^{-2})	3992.58 (982.54)	3072.95 (960.90)	3814.82 (1338.65)	3476. 64 (1004.41)
Ankle relative angle$_{\text{peak}}$ (°)	33.01 (11.56)	– 38.28 (10.53)	26.83 (21.76)	– 32.81 (17.61)
Ankle relative ang$_{\cdot\text{velx.peak}}$ (° s^{-1})	– 265.83 (59.49)	– 144.06 (31.61)	– 380.13 (396.72)	– 133.37 (130.87)
Ankle relative ang$_{\cdot\text{accx.peak}}$ (° s^{-2})	3945.70 (901.37)	3600.15 (980.31)	4064.11 (1631.29)	4288.51 (1444.96)
Knee relative angle$_{\text{peak}}$ (°)	23.34 (5.05)	34.80 (7.79)	26.41 (14.53)	34.00 (7.64)
Knee relative ang$_{\cdot\text{velx.peak}}$ (° s^{-1})	212.67 (45.61)	126.89 (54.04)	304.55 (336.51)	149.57 (69.73)
Knee relative ang$_{\cdot\text{accx.peak}}$ (° s^{-2})	2442.02 (790.31)	1471.46 (555.72)*	2653.00 (1208.64)	1881.10 (593.61)*
Hip relative angle$_{\text{peak}}$ (°)	– 10.43 (7.20)	– 28.13 (8.92)	– 8.01 (8.28)	– 26.49 (7.24)
Hip relative ang$_{\cdot\text{velx.peak}}$ (° s^{-1})	25.13 (26.75)	18.83 (42.97)	23.16 (55.67)	9.87 (44.98)
Hip relative ang$_{\cdot\text{accx.peak}}$ (° s^{-2})	1427.67 (433.01)	1125.03 (677.51)	1452.10 (549.74)	998.34 (429.49)

1. Stance phase: stance phase (SP) duration, stride duration (SDN), stride length (SL), stride speed (SS), as well as *2. Sub-stance phase parameters* for both early (ES) and late stance (LS) periods: the peak of ground reaction forces (GRF$_{\text{peak.}}$), required coefficient of friction (RCOF$_{\text{peak}}$), joint angles' (angle$_{\text{peak}}$), angular velocities (ang$_{\cdot\text{velx.peak}}$), accelerations (ang$_{\cdot\text{accx.peak}}$), and the minimum angle (angle$_{\text{min}}$) of the foot between pre- and post-exhaustion for all participants (N = 18)

$^{**}p \leq 0.01$. $^{*}p \leq 0.05$

§The peak values were obtained from whole ES (0% to 50%) and LS (50% to 100%) time normalized 5% periods of the SP. Other peak values were given from ES (5% to 25%) and LS (75% to 95%) 5% periods equivalent to average RCOF during 5% to 25% and 75% to 95% are critical for slipping events. $^{\#}$The RCOF$_{\text{peaks}}$ 1 and 2 were ignored (first 5% period) in the calculation by following the suggested RCOF$_{\text{peak}}$ retrieving method

steps resulted in lower impact on the ground, which was reflected in the decreased GRFz$_{\text{peak}}$. An increased post-exhaustion forward foot translation and momentum of the body at LS phase leads to the increment of whole_GRFy$_{\text{peak}}^{\S}$, when walking down an incine.

This post-exhaustive increased whole_GRFy$_{\text{peak}}^{\S}$ result also might have contributed to the increment of mean RCOF$_{\text{peak}}^{\S}$ value of 0.100, especially during the whole (50% to 100%) LS phase, which was significantly higher than the mean value of 0.033 at pre-exhaustion walking downwards on this dry metal surface. The RCOF$_{\text{peak}}^{\S}$ appeared to be high in that specific LS phase during post-exhaustive walking (Table 3, Figure 6b). A higher RCOF indicates higher potential for slip risks or loss of balance, but this $RCOF_{peak}^{\S}$ was calculated at the time point of $GRFz_{peak}$ for both ES and LS phase. It is worth noting that the $GRFy_{peak}$ is naturally higher at ES phase than at LS phase due to downward walking. Therefore, the slip risk with a higher RCOF is also higher at ES phase walking downwards.

Regarding the application of the RCOF values during evacuation while walking down a dry surface with 10° inclination, the $RCOF_{peak}^{\S}$ value of 0.342 and 0.322, respectively for pre-and post-exhaustion conditions, were found during the ES phase. These coefficient of friction (COF) values seem to be reasonable and comparable with the RCOF values reported in the earlier studies [12, 13] in the same degree of inclination on a dry vinyl and carpet with an average $RCOF_{peak}$ of 0.328. In this present study, the obtained mean $RCOF_{peak}^{\S}$ values (0.322) did not alter significantly during post-exhaustion walking downwards. Literature documented that there is an increase in antero-posterior shear force (GRFy) at ES when walking downhill, therefore, the RCOF is increased to maintain a safe walking. Taking shorter strides is a common strategy while walking downwards, and this can presumably reduce the frictional requirement at LS phase compared to the ES phase. In contrast, while walking up a 10° inclination, the shear force (GRFy) increases at LS but decreases at ES phase [10, 11]. Therefore, at LS phase, the higher $RCOF_{peak}^{\S}$ value of 0.350 and 0.297 were observed in previous study at pre-and post-exhaustion condition, respectively, on the same inclination and dry surface [7].

However, none of these $RCOF_{peak\ adopted}^{\#}$ values (Table 3, calculated following the method given in literature [47–49]) were altered significantly both at the ES and LS phases after exhaustion. When the available COF increases and becomes greater than RCOF, the probability of fall decreases [13]. A relevant study showed that when available COF is about 0.15, the probability of slip and fall is 0.8 (80%) [14], and the probability of a slip approaches to 0% with the $RCOF_{peak}$ at around 0.3. Based on the present and previous studies, the $RCOF_{peak}$ value of about 0.35 can be considered as the minimum COF needed between the shoe and floor interface on a dry, inclined metal surface for a relatively safe locomotion walking down a 10° inclination [7, 12, 13, 66]. However, higher RCOF values may be required, for example, on steeper inclines, surfaces built with different materials in the presence of contaminants such as water, oil [10, 12, 13], flammable substances, and ice [67] during winter [7].

3.3. Stance Phase (SP), Stride Length (SL), Stride Duration (SDN), and Stride Speed (SS) During Exhaustive Gait Down an Incline

The mean SL was significantly shorter, $t(17) = 2.67$, $p = 0.016$, during post-exhaustion walking trials (Table 3). The mean post-exhaustion $GRFz_{peak}$ during LS (75% to 95%) was significantly lower, $t(16) = 3.54$, $p = 0.003$. However, the post-exhaustion mean of $whole\_GRFy_{peak}^{\S}$ during LS (50% to 100%) was found significantly higher, $t(16) = -2.33$, $p = 0.033$ (Table 3, Figure 6a). Importantly, the post-exhaustion overall $RCOF_{peak}^{\S}$ during the LS (50% to 100%) period was found significantly higher, $t(16) = -2.51$, $p = 0.023$, too (Table 3, Figure 6b).

The mean post-exhaustion SL was significantly shorter (about 8.00 cm) than the pre-exhaustive walking trials. This is consistent with the shorter mean SP (0.09 s), SDN (0.03 s), and SS (0.02 m s^{-1}) (Table 3) during post-exhaustion walking down a 10° inclined walkway, which supported the hypothesis. Exhaustion may affect gait speed, which is an important slip potential factor. In this laboratory study, a regular "self-preferred" gait speed was chosen by the subjects. The results showed that the mean stance speed (SS) was about 1.5 $m \cdot s^{-1}$ in both pre-and post-exhaustion conditions. A falling event was not observed visually, except careful stepping on an incline, in either of the pre- and post-exhaustion conditions. However, the SL was significantly decreased post-exhaustion. Another study [65] also showed that balance while walking downwards could be maintained with careful and short steps arguably due to achieving through adjustments and corrections measures. These happen normally in our complex nervous and muscular control system, sometimes termed as a protective stepping strategy after exhaustion at 10° inclination. Thus, the reduced post-exhaustion SL is an indicator of careful steps and a contributor to reduce the slip potential walking downwards [12].

The decreased kinematic parameters indicate the cautious walking pattern due to exhaustion and leg LMF. A plausible explanation of the significantly shorter post-exhaustive SL might be due to a shortened reciprocal swing phase as an adjustment of shorter steps to maintain balance and, thus improved the stability during the post-exhaustive walking trials. The investigators in this study observed the participants with a more prudent gait during exhaustive walking trails evidenced by the reduced SL, which may have contributed to the shortened SP, SDN, and SS, thus may increase the cadence. The decreased SL supports the hypothesis on careful steps, which might have affected the $GRFs_{peaks}$, but helped to maintain the post-exhaustive walking balance in the downward direction [16, 17]. The significant SL decrease indicates the cautious steps walking downwards at the post-exhaustive state, which may lead to possible occurrence of slip and fall events. Nevertheless, in this study, whatever the effects have had on these differences observed in the variables remain to be studied further in real evacuation situations.

3.4. Joint Motion: Angles, Velocities, and Accelerations During Exhaustive Gait Down an Incline

None of the lower limb joint's peak angles, angular velocities, and accelerations were significantly affected, when walking downwards due to whole-body exhaustion, except the knee $ang._{accx.peak}$ (Table 3, Figures 7, 8, and 9). The post-exhaustive knee $ang._{accx.peak}$ significantly, $t(13) = -3{,}672$, $p = 0.003$, increased during LS period (Table 3, Figure 9c). A possible explanation of these non-significant results is that walking downwards is not as challenging, regarding physical workload as upwards even after reaching a whole-body exhaustion following a stair ascending task. In an exhausted state, the body was still able to generate the necessary power and kept a required inter-segmental relationship to maintain the balance when walking in the downward direction. These non-significantly constrained post-exhaustion joints motion and EMG activity results indicated that whole-body exhaustion did not equally affect walking gait downwards even after an exhaustive stair ascent task, as it did while walking upwards [7]. The body's protective mechanism through joint stiffness control may explain the mechanism, which might have helped to maintain the required balance in response to walking downwards in an exhaustive physical state. The joint moments might have well distributed and coordinated during this short SP with non-significantly altered joint kinematics in spite of whole-body exhaustion [12].

Walking downwards is more common in the perspective of building's evacuation. The kinesiological demand seems to be much less when walking downwards than upwards on a slope. In a previous study, from the same data set, post exhaustive walking gait analysis in an upward direction showed LMF on the major thigh (vastus lateralis) and lower leg (tibialis anterior) muscles following the stair ascending at maximum speed until exhaustion. The LMF and exhaustion constrained most of the kinetic and kinematic parameters including the vertical

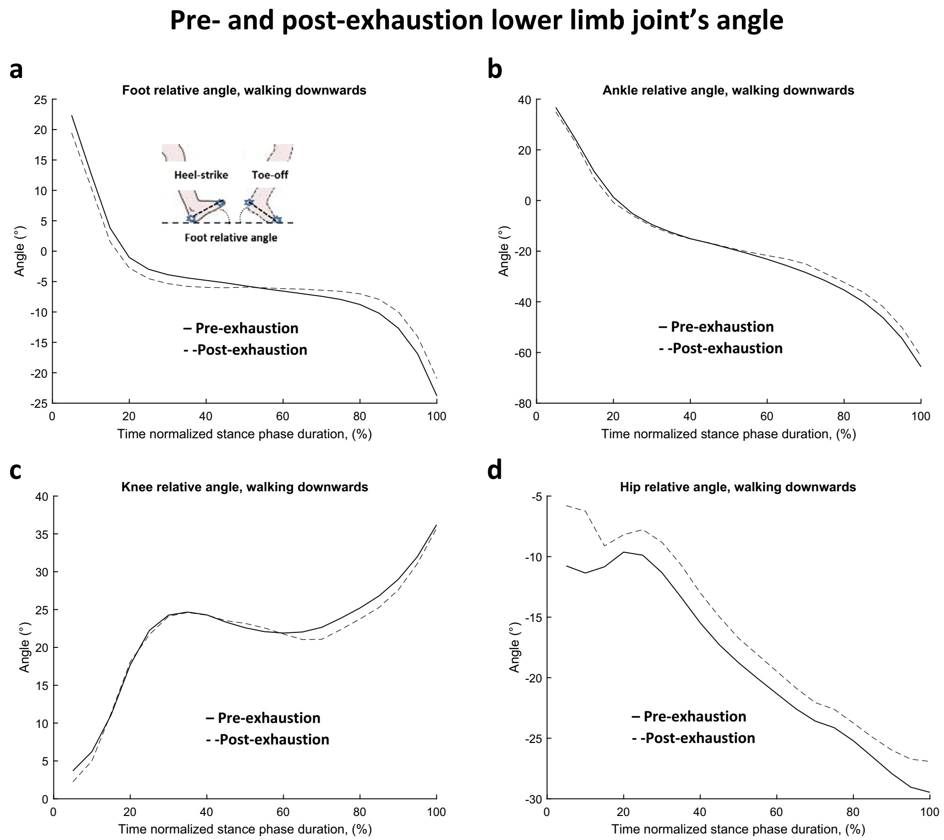
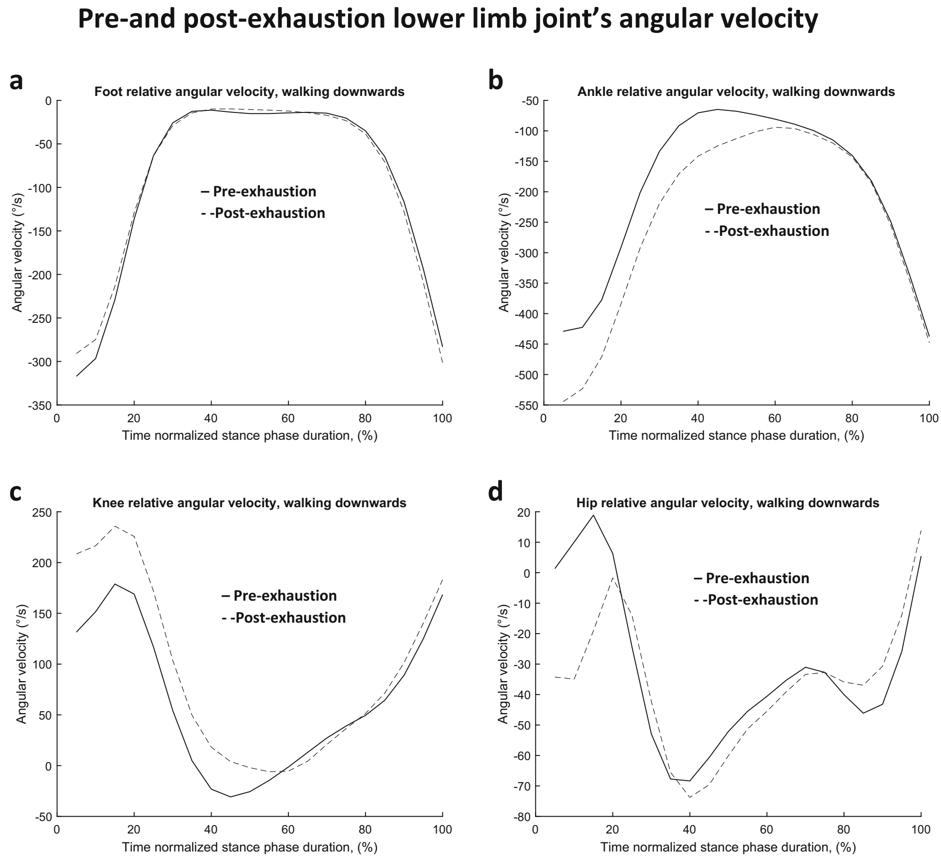


Figure 7. The mean foot (a), ankle (b), knee (c), and hip (d) relative angles during time-normalized stance phase (SP) 0%, initial contact (IC) to 100%, final contact (FC) pre- (solid lines) and post-exhaustion (dashed lines) when walking down a 10° inclined walkway.



Pre-and post-exhaustion lower limb joint's angular velocity

Foot relative angular velocity, walking downwards

Ankle relative angular velocity, walking downwards

Knee relative angular velocity, walking downwards

Hip relative angular velocity, walking downwards

Figure 8. The mean foot (a), ankle (b), knee (c) and hip (d) relative joint angular velocities during time-normalized stance phase (SP) 0%, initial contact (IC) to 100%, final contact (FC) pre- (solid lines) and post-exhaustion (dashed lines) when walking down a 10° inclined walkway.

and antero-posterior shear forces during ES and LS phases when walking up a 10° slope. That analysis showed that the post-exhaustive SP, SL, and SDN significantly shortened, which support a cautious gait pattern when walking upwards on an inclined path. In that study, the detected significant changes in the post-exhaustive gait kinematic parameters including the alterations in foot positions ascertained a higher kinesiological demand when the participants walked up the same degree of inclination [7].

Conversely, the biomechanics analyses in this study suggested that an exhaustive body had a non-significant impact on its joint's kinematics during gait on a downward slope. Hence, no slip and fall accidents occurred during either of the pre-and post-exhaustion walking downwards trials [13]. Based on this study outcomes, it seems that walking downwards is physically and biomechanically less

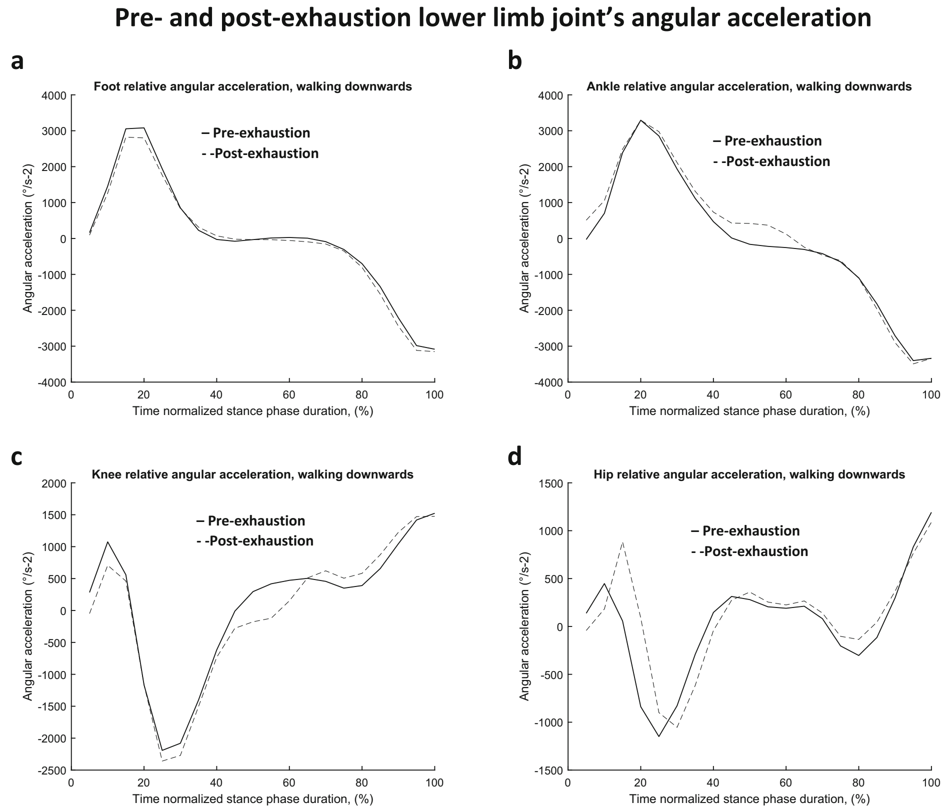


Figure 9. The mean foot (a), ankle (b), knee (c) and hip (d) relative joint angular accelerations during time-normalized stance phase (SP) 0%, initial contact (IC) to 100%, final contact (FC) pre- (solid lines) and post-exhaustion (dashed lines) when walking down a 10° inclined walkway.

challenging than up an incline, when comparing the results from that previous study results and analysis [7]. The reduced kinesiological demand when walking down an incline might have easily propelled the body forward compared to walking upwards, however, the laboratory findings need to be further validated in real emergency evacuations. The observed kinematic results evidenced that the exhaustive walking in downward was manageable with the residual physical effort and thus, without significantly constraining many gait kinematics parameters even after an exhaustion.

It is presumably suggested also that a cautious gait with having an awareness of the situation avoided any unprecedented slips and fall events. Additionally, the plausible less kinesiological demand when walking downwards may have contributed to these non-significant results that have been observed mostly on the kinematics of the leg joints. However, the other obtained biomechanics results partially supported the hypothesis of this study, that the overall exhaustion and

LMF in the legs may affect the gait pattern and stability [65] through decreasing the gait SL, $GRFz_{peak}$, and while increasing the $GRFy_{peak}$. LMF might have destabilized the walking pattern leading to shortening the durations of SP and SL. This unstable walking pattern indicates the potential risks of slip-induced fall accidents [68]. However, the effects observed in this present laboratory study, on human postural control strategies and balance reactions, which need to be investigated further in real situations.

This study focused only on one step, the SP on the force plate. The post-exhaustion mean SP duration (≈0.65 s) was very short. The length of this specially constructed inclinable walkway is relatively short compared to regular walking lengths on level surfaces. This short SP has limitations to obtain some of the gait kinematic parameters, and the data from one-step might not be sufficiently representative. The use of a second force plate would have enabled us to explore more of the fatigued gait biomechanics from both sides on an incline surface [25, 69]. The methodology of the reflective markers' placements can involve a degree of positioning variance and the equations used for calculations of the parameters. However, the results of this study revealed gait variable changes within SP and helps to understand the stability and locomotion risks after physical exhaustion. The subjects in this study were healthy and relatively fit younger adults. A relatively limited number ($N = 18$) of volunteers with similar anthropometric characteristics participated in this study due to the time-consuming process to collect the data. The present sample size is comparable to the number of participants in other similar kind of published biomechanical studies [10, 13] in laboratory settings. It is also important to look at the effects of various age groups with different physical fitness in future studies.

Importantly, the findings in this study with synchronized measurements provide new insights on the relationship between whole-body exhaustion, legs' LMF and gait pattern changes within the SP, which may increase the risks of slips, trips and fall accidents [20], and injuries in the context of stressful evacuation situations on an incline. The reported results can be considered and integrated into both existing and new evacuation models to increase the accuracy of estimation and improve the assessment of safety measures, and the success of emergency evacuations and rescue operations. Furthermore, orthopedic and rehabilitation health professionals could be able to use these data for comparing the effect of their treatments, interventions in different phases of injury rehabilitation. Also, these results might be helpful assessing the gait biomechanics of elderly and physically challenged persons and can contribute to ensuring work-safety on a slope.

4. Conclusion

Physical exhaustion was achieved and confirmed both objectively by the mean high blood lactate level of 14.4 mmol l^{-1} and subjectively with a high rating result 18, on the Borg's scale at the end of ascending stairs at maximum speed. The electromyography (EMG) results also supported the claim of local muscle fatigue (LMF) in the legs objectively at the end of stair ascent. Post-exhaustion walking gait biomechanics showed that kinetic profiles seem to be more affected than kinematic variables during walking down a 10° slope. Whole-body exhaustion and leg's LMF significantly shortened the stride length (SL) and lowered the normal peak ground reaction normal force ($GRFz_{peak}$). Additionally, the significantly increased antero-posterior shear force ($GRFy_{peak}$) may lead to a higher required coefficient of friction (RCOF) needed at the shoe and floor interface to support a safe human locomotion walking down an incline. Whole-body exhaustion potentially causes gait perturbation, which may result fall accidents, due to the changes on the biomechanics parameters including GRF profiles, RCOF and SL. None of the post-exhausted leg joints' peak angles, foot minimum angles, angular velocities, and accelerations were affected significantly, which indicated a low kinesiological demand when walking downwards compared to upwards on an inclined surface. The decreased muscle activity when going down a 10° inclined walkway was reflected also in gait EMG results.

The observed gait biomechanics results in this study can potentially be used by health-professionals as reference data on an incline to make possible comparisons with the gait of the injured and disabled patients, and to reorganize treatment and rehabilitation plans and protocols to improve their gait patterns. This study contributes to the understanding of the relationships between exhaustion and gait biomechanics outcomes of walking down an incline. The findings can help the fire engineers, safety engineers, architects, and designers in reorganizing plans and redesigning evacuation facilities and roofs in buildings and deep underground infrastructures. These results may help to decide the characteristics of exits, resting planes, or roofs, for example, when it comes to deciding the flooring systems including surface materials, inclinations, distances, and widths of the walkways. The planning and designing of inclined exits, working or walkway surfaces at higher levels of buildings need a high COF similar to the obtained values in this study in order to prevent fall accidents, and to keep a smooth flow of evacuation. According to this present study and previous studies, the available COF of 0.350 seems to be the required coefficient of friction (RCOF) to reduce slips and falls both in physically normal and exhaustive conditions on 10° inclinations for dry surfaces.

This laboratory study demonstrated changes in gait kinetics, kinematics, and the mechanisms for slips and falls from a limited number of healthy and young homogenous participants on a downward incline. Further studies in the field and laboratory with a larger sample size including different age groups, persons with and without carrying an extra load, with disabilities are needed. Moreover, the present modeling of evacuation does not usually include human physiological capacity, exhaustion level, gait biomechanics, slope inclination, surface frictions etc. This study findings related to exhaustion, degree of inclination, width and length of the exit walkways can be integrated into both existing and new evacuation models in future. More gait data over the full stride cycle need to be collected on various degrees of inclination post-exhaustion, so that a mathematical model can be formulated to establish the relationship between exhaustion levels and degrees of inclination related RCOF between the shoes, various surfaces with or without contaminants, and foot forces to prevent fall-related injuries during evacuation.

Acknowledgements

The authors gratefully acknowledge the commitment and dedication of the participants; Stefan Lindgren, Jens Nirme, and Humanities Lab, Lund University for transferring the motion capture system to the Department of Design Sciences; Lars Nilsson, Medotemic AB, Sweden for assisting with the draft of the ethical application in Swedish; Åsa Tornberg, Lund University for providing the EMG equipment; Siyeon Kim, Korean Institute of Industrial University, South Korea for assisting with data collection.

Author Contributions

AH, CG, and JN jointly conceived, designed the research. AH and CG led the study and conducted experiments. AH and AN analyzed the data. AN, AH, and CG contributed analytical tools and methods. AH mainly wrote the manuscript, while CG, AN, and MM helped. All authors read and contributed to drafting and improving the manuscript. They all reviewed and approved the final version.

Funding

Open access funding provided by Lund University. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. However, this paper is based on an extended study related to the Stair Ascending Evacuation Project (TVBB-3192) sponsored by the Swedish Fire Research Board (Brandforsk) and the Swedish Transport Administration (Trafikverket). Authors also extend thanks to the project leader, Enrico Ronchi.

Declarations

Conflict of interest The authors declare no conflict of interests.

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