Original

The Influence of Carrying Anterior Load on the Sagittal and Frontal Plane Kinematics of Lower Extremities during Stair Ascending

Smadi O.[1*], Abu Alim M. A.[2], Masad I. S.[3], Almashaqbeh S.[4]

[1]PhD, Department of Biomedical Engineering, Faculty of Engineering, the Hashemite University, Zarqa, 13133, Jordan
[2]PhD, Department of Sport Sciences, Faculty of Physical Education, Yarmouk University, Irbid, 21163, Jordan
[3]PhD, Department of Biomedical Systems and Informatics Engineering, Hijjawi Faculty for Engineering Technology, Yarmouk University, Irbid, 21163, Jordan
[4]MSc, Department of Biomedical Systems and Informatics Engineering, Hijjawi Faculty for Engineering Technology, Yarmouk University, Irbid, 21163, Jordan

*Corresponding author: O. Smadi
Department of Biomedical Engineering, Faculty of Engineering, the Hashemite University, Zarqa, 13133, Jordan
E-mail: othman.smadi@hu.edu.jo

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ABSTRACT

Background: Anterior load carriage is a one of the commonly performed activities in some industries. Stair climbing while carrying anterior load significantly alters different biomechanical mechanisms that can potentially affect the musculoskeletal function of the lower extremities.

Objective: The study aims to assess the effect of carrying an anterior load (20% of body weight) on lower extremity kinematics during the kinematical phases of stairs ascent (weight acceptance, pull up, forward continuance, and swing phase).

Material and Methods: In this experimental study, data were collected through the use of a custom made wooden staircase and OPtiTrack motion capture system was composed of 12 infrared cameras and a per modeled reflective marker set. Sixteen female college students volunteered to conduct two tasks of ascending stairs with and without an anterior load of approximately 20% of their body weight. The collected frontal and sagittal plane lower extremity joint angles were calculated using MATLAB software (version R2015a). Statistical comparison between the two study tasks was made using IBM SPSS Statistics software (version 25.0; SPSS Inc., Chicago, IL, USA).

Results: Based on the results, there is significant difference (p-value < 0.05) between the two study tasks during ascending stair phases in all three sagittal plan lower extremity joint angles.

Conclusion: Anterior load carried during stair ascent causes participants to depend more on the hip joint (higher flexion angles) compared to stair ascent without loads, which may increase the risk of falls and injuries, and the importance of muscle-strengthening activities and highlight the use of appropriate technique during load carriage.

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Keywords

Knee and Hip Joints; Anterior load; Gait; Kinematics; Time and Motion Studies; Stair Climbing; Range of Motion

Introduction

Low physical activity and sedentary behavior of young adults have been linked to a higher risk of injuries and lower quality of life. The global standards of modern quality of life concern about not only lowering the risks and prevalence of health problems such as obesity, diabetes, and arthritis but also the efficiency of accomplishing daily tasks without pain and discomfort in addition to enjoying healthy leisure times [1-3]. A significant cause of pain and injuries, at performing daily tasks, is the lack of muscle skeleton strength. Previous research studies have shown a direct link between lower extremity strength and stability of locomotion, providing sufficient motor patterns and generating balanced stress through the kinetic chain [4]. Altered moving patterns apply higher stress on joints, leading to discomfort and pain alongside with higher risk of injuries. Previous research studies showed that locomotion's associated pain and discomfort has significantly lowered people's physical activity while performing daily tasks [5, 6].

One of the most frequent tasks with a significant impact on promoting levels of physical activity, requiring the double metabolic cost to accomplish is stair climbing (comparing with level walking) [7, 8]. Stair ascent is selected to place extra load and to require higher flexion angles of the lower extremity compared to ground walking. Thus, weakness in the lower extremity altered the moving strategy during stair ascent; for example, while lifting the body to the next step, both knee and hip joints extension are responsible for accepting the body weight, i.e., at the presence of lower extremity weakness, the body depends more on the hip joint to maintain a balanced and stable movement, placing an increased stress and moments. Two balance strategies have been proposed to withstand perturbation, including the ankle strategy and the hip strategy. The ankle strategy considered the based motor control to counter any changes in the body's center of gravity and to maintain balance control during essential movements and small perturbation such as stepping on uneven ground or maintaining a quiet standing. The hip strategy addressed larger perturbation as the hip is a multidirectional joint that initiates the swaying and adjusts the trunk to maintain the center of pressure within the limits of stability. Due to extra loads or weakness in the muscle skeleton system, a hip balance strategy is activated to correct altered moving patterns. The previous alteration has been linked to increased trunk tilt during stair ascent, raising the risk of falling [9]. The high rates of fall and related injuries across ages, health status and gender during stairs climbing are major health concern [10-13].

Furthermore, during the daily tasks, stair climbing is typically performed while carrying extra loads such as babies, grocery bags, resulting in further demands on the lower extremity and also raising the risk of falls and related injuries [14, 15]. A study conducted by Hall and collages (2013) showed that when participants were loaded with a (13.6 kg) in the front or the back of their bodies, representing approximately 20% of their body weight, the external knee adduction moments increased compared to locomotion without loading. Whereas, stair ascent had a significant increase in knee adduction moments compared to stair descent task [16]. The impact of symmetric and asymmetric load conditions on the kinematics of stair gait has been investigated by Wang and Gillette (2017). The results of their study showed that when participants were asked to carry a 20% unilateral (asymmetrical) external loads during stair ascent, they demonstrated a significant increase in moment magnitudes of trunk bend, hip abduction, and external knee varus [15]. The impact of postural stability and balance control, while moving with an external loads, has been reported to overall intensification in center of pressure projection and sway speed thus requiring greater effort to maintain balanced moving patterns [17-19]. In summary, the task of stair ascending whiles carrying an external load increases the demands to maintain stability. Thus, the body tends to decrease distal joints range of motion and depend on proximal larger joints like the hip to keep the body's center of mass within the base of support during the ascend. The use of a rigid movement pattern during stair ascending to withstand extra loads might increase the risks of injuries and falls.

Many studies have investigated the concern of stair falls in the young adult population due to daily responsibilities and tasks of carrying using stairs. Stair injuries have caused higher risks of mortality or significant injuries such as traumatic injuries to the brain and integral joint fractures than level walking [20-25]. A better understanding of the requirements, based on motor control and strategy balance to maintain stability and withstand the extra loads during stair ascent, could help better analyze the risk behavior, eliciting stairs falls during ascending.

Thus, the purpose of the current study is to assess the effect of carrying an anterior load on the kinematics of lower extremities in sagittal and frontal planes during stairs ascent selected phases as follows: weight acceptance, pull up, forward continuance, and swing phase.

Material and Methods

Participants

In this experimental study, a group of 16 female college students aged between 19 and 25 years old, were recruited. Mean (M) and standard deviation (SD) demographic data were as follow: age (M = 21.53 years, SD = 1.40), weight (M = 58.7 kg, SD = 6.02), height (M = 169.1 cm, SD = 4.82), Body Mass Index (BMI) (M = 22.36, SD = 1.85). Participants' inclusion criteria included free of pain, injuries and without any surgeries during past year and balance issues due to illness or health conditions. Also, participants were asked to report if they had any problems completing the study tasks at any point during data collection, and they could safely and successfully complete the assessments.

Testing Protocol and Equipment

This study's stair ascending tasks were performed on a four steps costume made staircase (step height 17 cm, and a 28 cm tread depth). Two stairs ascent tasks were assessed and compared as follows: stair ascending with no load and stair ascending while carrying an external anterior load of 12 kg, representing 20% of participants' body weight according to previous research studies [16, 26]. Those studies showed that external loads of 10 to 20% of subjects' body weight during locomotion had a significant kinematical and kinetical alteration compared to non-loading conditions. The current study's external load contained two sand sacks (6 kg each) and was fixed anteriorly into a custom-made vest. The load is positioned anteriorly and approximately at waist level to avoid the variations in the carrying method between participants, and to prevent introducing any postural sway [27].

A brief explanation of the purpose and procedures of the study were presented to all participants. Likewise, the subjects' confidentiality and anonymity were explained and ensured, and participants were asked to sign an informed consent that also included participants' demographic data. For data collection participants wore a motion-capture suit where markers were attached to left and right ASIS (Anterior Superior Iliac Spine), bilateral hips, thighs, knees, shanks, ankles, heels, and toes, as shown in Figure 1. All stair ascending tasks were performed barefooted, and tasks were randomized, and each task was performed three times. Stair ascent was initiated with the participant's left leg on the first step, followed by the right leg at the next step and continued step over step.

Kinematic and statistical data Analysis

A 3D motion analysis system (Optitrack, Natural Point Inc., USA) with 12 high-resolution cameras (Prim 13 Optitrack, Natural Point Inc., USA) was used to obtain sagittal and frontal plane kinematic data during the testing tasks. Kinematics of the participant's hip, knee, and ankle joints of the dominated leg (the right leg for all participants) were analyzed in the frontal and sagittal planes during

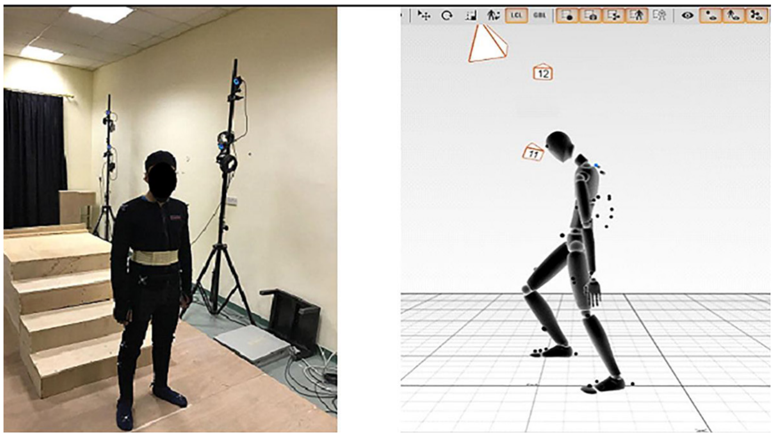

Figure 1: The experimental setup showing the used suit with the attached reflective markers (left), and the equivalent skeleton illustration by the optical motion capture software (MOTIVE) (right).

stair ascending study tasks. The related angles were defined, as shown in Figure 2. The kinematic analysis included a stair gait cycle during ascending, which started from the right foot's contact with the second step until the same foot's contact at the fourth step.

Tracked position data of all markers during the gait cycle was exported to Microsoft Excel 2016 and were read by a custom-designed code developed in MATLAB (Release R2015a, MathWorks Inc, USA). Gait cycle for each participant was divided in to four stages (weight acceptance, pull up, forward continuance, and swing stages), determined by tracing the toe marker position on left and right feet. According to participants stair ascending averaged data, the stair gait cycle was categorized as follows: weight acceptance stage extended from the first contact and ended at 17% of the stair gait cycle, followed by the pull-up stage 37% of the stair gait cycle. The remaining part of the gait cycle was divided between the forward continuance stage and the swing phase, persisted till 65% and 100% of the gait cycle, respectively.

Independent t-tests were used to indicate any significant difference between the two ascending tasks (with and without carrying an ante-

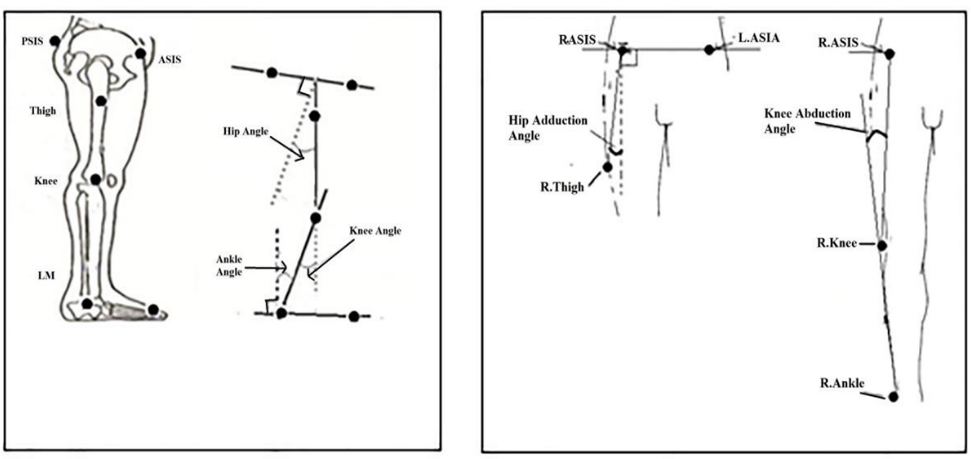

Figure 2: Lower extremity joint angles calculation definition.

rior load) ($p \leq 0.05$). Statistical analyses were performed using SPSS software (version 25.0; SPSS Inc., Chicago, IL, USA).

Results

The results of lower extremity at the sagittal plane indicated statistically significant difference in flexion angles of the ankle, knee and hip during stair climbing between the two analyzed tasks (carrying loads, and without load) (Table 1).

More specifically, participants had a higher hip flexion angle while carrying anterior load compared to non-loaded stair ascent tasks and at all phases, but the forward continuance phase. Similarly, the knee flexion angle was significantly higher in carrying the anterior load during all stages, except the maximum knee flexion angle during the forward continuance stage.

The minimum knee flexion angle during the swing phase was significantly smaller when the subjects ascended the stairs while carrying the anterior load. Also, the ankle dorsiflexion angle was considerably lower when climbing stairs while carrying the anterior load. In comparison, the ankle plantarflexion angle was significantly smaller when ascending the stairs, carrying an anterior load as well, except in the pull-up and forward continuance stages. Furthermore, the frontal plane kinematics' statistical analysis indicated that a significant increase in the hip abduction angle during stair ascending was observed only in the pull-up and forward continuance stages, as shown in Table 2.

Significant difference in the knee abduction and adduction angles were only observed during the weight acceptance stage. Figure 3 shows the full behavior of the ankle, knee, and hip joints angle during the complete stair ascending gait cycle in the sagittal plane of the

Table 1: The mean (standard deviation (SD)). Sagittal Plane angles observed at the ankle, knee, and hip joints with load and without load, during stair ascending.

Angles			Hip	Knee	Ankle
Weight Acceptance	Max.	Without load	37.75(8.88)	67.74(5.05)	28.88(4.62)
		With load	*47.33(8.15)	*69.77(4.33)	*27.25(4.15)
	Min.	Without load	25.60(7.48)	52.08(6.73)	23.26(4.54)
		With load	*33.56(7.72)	*54.47(6.23)	*21.01(4.73)
Pull Up	Max.	Without load	25.05(7.50)	51.24(6.76)	27.30(4.86)
		With load	*32.95(7.75)	*53.80(6.26)	*25.96(4.48)
	Min.	Without load	7.69(6.33)	22.47(4.55)	18.82(4.58)
		With load	*10.25(8.74)	*23.63(4.16)	18.61(4.36)
Forward Continuance	Max.	Without load	8.49(6.92)	30.56(8.01)	22.93(5.20)
		With load	10.23(8.95)	*26.74(4.80)	*21.86(5.05)
	Min.	Without load	(-0.47(8.25))	18.38(4.63)	(-5.25(8.32))
		With load	0.99(9.50)	18.14(4.41)	(-6.22(6.53))
Swing	Max.	Without load	41.20(9.17)	90.95(6.00)	25.15(5.17)
		With load	*50.07(8.50)	*94.04(5.42)	*23.20(5.57)
	Min.	Without load	3.49(9.96)	29.76(10.38)	(-8.49(9.01))
		With load	3.86(9.96)	24.21(6.59)	*(-12.00(8.18))

*A significant difference ($P < 0.05$) between the "without load" and "with load" values.

Table 2: The mean (standard deviation (SD)). Frontal plane angles observed at the knee and the hip joints with load and without load, during stair ascending.

Angles			Hip	Knee
Weight Acceptance	Max.	Without load	0.81(4.21)	1.59(5.82)
		With load	0.28(6.38)	*5.70(7.50)
	Min.	Without load	(-3.62(3.93))	(-3.19(5.30))
		With load	(-5.61(7.53))	*(-0.96(5.27))
Pull Up	Max.	Without load	11.45(4.05)	(-0.18(3.65))
		With load	*15.26(7.67)	0.62(4.47)
	Min.	Without load	(-0.13(4.133))	(-3.33(3.85))
		With load	(-0.05(6.047))	(-2.69(4.10))
Forward Continuance	Max.	Without load	12.50(4.11)	0.69(3.16)
		With load	*17.96(8.25)	(-0.47(3.58))
	Min.	Without load	4.46(3.06)	(-2.99(2.96))
		With load	7.19(7.89)	(-3.15(3.42))
Swing	Max.	Without load	5.63(3.40)	18.04(7.77)
		With load	7.71(7.74)	19.01(10.94)
	Min.	Without load	(-6.70(5.45))	(-5.40(6.56))
		With load	(-8.22(7.60))	(-4.77(5.45))

*A significant difference ($P < 0.05$) between the "without load" and "with load" values.

two studied tasks (with and without carrying 12-kg anterior load during stair ascent). Figure 4 shows the full behavior of the knee and hip joints angles during the complete gait cycle in the frontal plane for the same two study tasks mentioned above.

Discussion

The current study aimed to assess the lower extremity kinematics in the frontal and sagittal planes during stair ascent with and without carrying approximately 20% of body weight in the form of an anterior load. The obtained results give a better insight on the body postural adaptation strategy to withstand external loads while ascending stairs. The current results of the lower extremities' joints angles are in consistent with previously published research studies investigating the joints kinematics of regular stair ascending without carrying any load [28-31]. Nevertheless, some differences in the joints angle values among studies in the other literatures and the current work could be because of methodological differences such as stair dimensions and inclination, subject characteristics, and calculating the joints angles. However, the obtained joints curves showed a high degree of agreement with most of the previous literatures.

The results of this study showed a lower ankle dorsiflexion angle when ascending stairs while carrying an anterior load compared to ascending the stairs without loading. The mean ankle dorsiflexion angle while carrying anterior load during weight acceptance stage was 27.25 compared to 28.88 with no load. During the pull up stage, the mean ankle dorsiflexion angle was 25.96 while carrying anterior load compared to 27.30 with no load. Similarly, for the forward continuance stage, the mean ankle dorsiflexion angle was 21.86 and 22.93 with loading and without loading conditions,

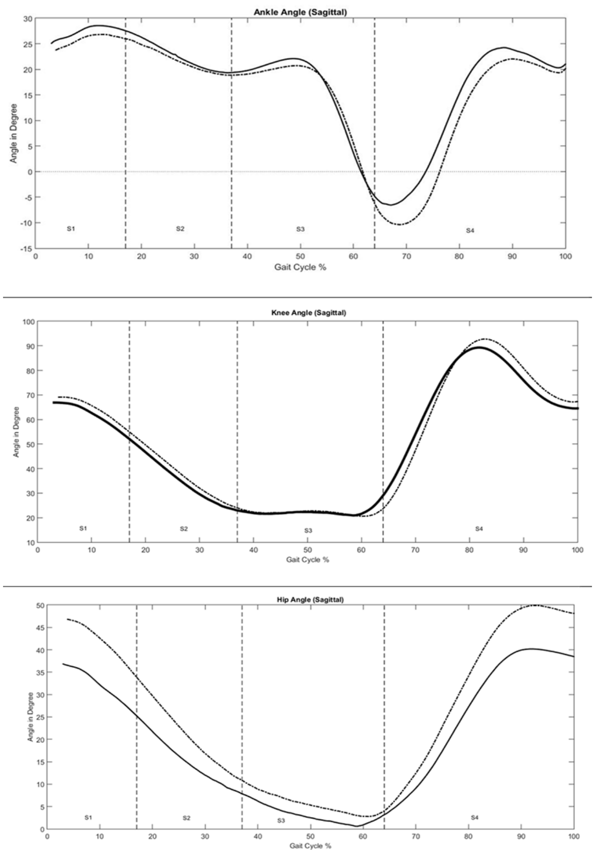

Figure 3: The mean values of the ankle, knee, and hip joints angles (top, middle, and bottom graphs, respectively) in the sagittal plane during stair ascent for subjects carrying (-.-) and not carrying (–) anterior load. (S1 – S4 represent weight acceptance, pull up, forward continuance, and swing stages, respectively).

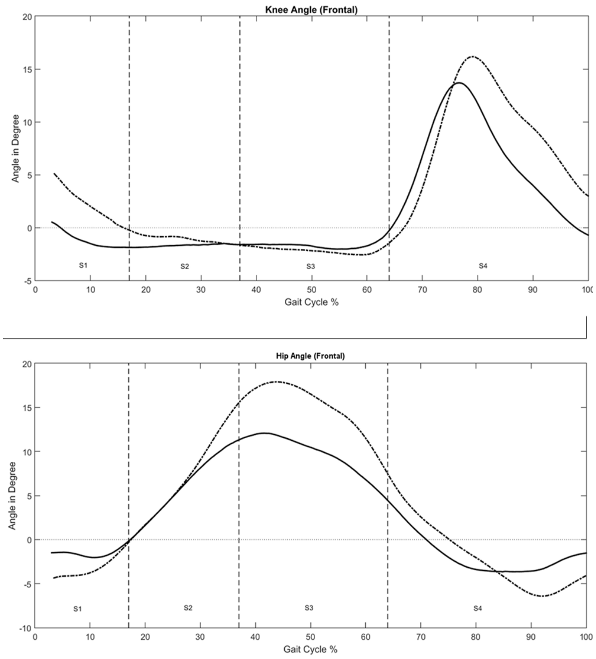

Figure 4: The mean values of the knee and hip joints angles (top and bottom graphs, respectively) in the frontal plane during stair ascent for subjects carrying (-.-) and not carrying (–) anterior load. (S1 – S4 represent weight acceptance, pull up, forward continuance, and swing stages, respectively).

respectively. During swing phase, the results showed a lower mean ankle dorsiflexion angle when ascending the stairs carrying the load (23.20) compared to the angle when ascending stairs without loading (25.15). The decreased ankle dorsiflexion angles, caused by carrying the anterior load, have been shown to affect the body dynamic stability, which requires some postural adjustments at the hip and knee joints in the sagittal and frontal plane to maintain stability while carrying an anterior load [32].

The current results also showed an increase in the maximum hip flexion angle, the minimum hip flexion angle, the maximum knee flexion angle, and the minimum knee flexion during the weight acceptance and the pull up phases while carrying an anterior load. Furthermore, the knee abduction angle had an increase in the frontal plane during the weight acceptance phase, while the knee adduction angle decreased. On the other hand, at the pull-up phase, the hip abduction angle was higher when carrying the load than without the load condition. The adopted posture with the hip and the knee in a more flexed position and the knee in a more abducted position, especially during weight acceptance and pull up stages, results in lowering the center of gravity towards the ground, which can enhance the stability in response to the carried weight. However, this could place higher demands on the lower extremities' muscles and joints. In the forward continuance phase, although there was no significant difference in hip flexion angle and the knee flexion angle was significantly lower, the hip abduction angle was higher (M=17.96, SD=8.25) when carrying load compared to (M=12.50, SD=4.11) without load. Hip abduction tends to have a critical role in adjusting the posture to maintain balance at the terminal stance while the collateral leg is in the swing phase.

Although, higher flexion angles have been reported to be associated with higher stress on joints surface and increased more demands on muscles to maintain stability, which could elicit pain and discomfort during locomotion [1], they, at the hip and knee joints, tend to stabilize the body to withstand the extra loading by lowering the body center of mass during stair ascending to withstand the extra loading. In the current study, participants had significantly higher flexion angles when carrying the anterior loads during stair ascent than non-weighting loading stair ascending task. Similar results in healthy young participants were reported in the study of Tseng & Liu [18]. Their results addressed a significantly higher increase in hip and knee flexion angles while carrying loads by handheld method during stair ascending than compared to the non-loading condition.

Frontal plane kinematic analysis of the current study showed that the maximum hip abduction angles which peaked during forwarding continuance phase significantly differed between stair ascent with and without anterior load carriage (M= 17.96, SD=8.25) and when loaded (M= 12.5, SD = 4.11). The current study's results were in agreement with the study of Wang and Gillette (2017). The results of Wang and Gillette (2017) showed that when participants were asked to carry a 20% external loads during stair ascent, a significant increase was observed in trunk tilt, hip abduction and knee adduction monuments. Previous studies had reported that both knees and hip joints had been significantly altered when participants had to ascend stairs while carrying about 20% external loads [14, 15]. Moreover, it has been described that low strength of the hip abductors impacts the sufficient moments to counteract the pelvic adduction on the contralateral side, leading to a possible mechanically inefficient stair ascent [12].

Differences in maximum knee adduction/abduction angles peaked during the swing phase, whereas no significant differences were founded between loaded and non-loaded stair ascent current study tasks. These results contradicted some previous studies [16, 17, 25]. However, the current data have had an increase in knee abduction angle and a decrease in knee adduction angle during the weight acceptance phase related to the differences in the research protocols, joint angles calculations, loading position, and stair ascending gait phases categorization.

Conclusion

In situations where an extra anterior load is carried (e.g., Marching bands, carrying a baby, school bags) movements, postures, and ability to withstand such loads may be affected. Anterior loading of the body presents a challenge that might increase the risk of falling and trapping while ascending a staircase by altering the location of the body's center of gravity. The results of this study concluded that the anterior carriage, of almost 20% of participants' body weight, could affect their balance strategies. The current study also showed that in order to withstand anterior load carriage and maintain balance, participants depended more on the hip joint (higher flexion angles) compared to the stair ascent without loads, which may raise the importance of increasing strength and highlight the use of appropriate technique during load carriage. The results of this study could contribute to the fundamental understanding of how added anterior loads influence human balance and stability status while ascending stairs. Future work shall include investigating the effect of these modifications on the lower extremities joints loading, in addition to addressing the biomechanical risk factors of trapping and sliding during stair ascending.

Acknowledgment

This study met the ethical and safety standards and accomplished the ethics code of Yarmouk University that followed the ethical principles of the Declaration of Helsinki Human rights. The Research Ethics Committee has approved all procedures and consent forms related to this study's protocol at the Department of Biomedical Engineering at Yarmouk University.

Conflict of Interest

None

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