European Review for Medical and Pharmacological Sciences 2024; 28: 3493-3502

Examining BMI-knee angle relationship in healthy young adults during stair ambulation using Kinovea® software

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ABSTRACT. – OBJECTIVE: This study explored the correlation between body mass index (BMI) and knee angle during ascending and descending stairs in healthy young adults. The hypothesis was that higher BMI would be associated with altered knee angles during stair ambulation.

PATIENTS AND METHODS: Participants' (n = 43) demographic characteristics, including age, height, weight, BMI, leg preference, and thigh lengths, were recorded. Gait parameters, such as cycle duration, stride phase, velocity, and knee angles, were analyzed using Kinovea® software. Inferential statistical tests, including ANOVA, *t*-tests, and correlation analysis, were performed to explore the relationships and differences between variables.

RESULTS: No significant effect of BMI on knee angle was found [ascending stairs: F (2, 40) = 0.75, $p = 0.47$; descending stairs: F (2, 40) = 0.58, $p = 0.56$]. However, gait parameters differed significantly, with shorter cycle duration during ascending stairs (M = 4.52 s, SD = 0.76 s) compared to descending stairs (M = 4.72 s, SD = 0.81 s). The stride phase varied across BMI categories [F (2, 40) = 3.82, $p < 0.05$], with the ideal weight group (M = 47.12%, SD = 3.21%) exhibiting a distinct stride phase. Positive correlations were found between knee angle and thigh length difference during ascending (r = 0.42, $p < 0.05$) and descending stairs (r = 0.38, $p < 0.05$).

CONCLUSIONS: This study demonstrated that BMI did not significantly affect knee angle during stair ambulation. However, gait parameters such as cycle duration, stride phase, and velocity differed between ascending and descending stairs. The positive correlation between knee angle and thigh length difference suggests that individuals with more significant thigh length differences may exhibit larger knee angles during stair climbing. The findings of this study have clinical implications for rehabilitation programs and the design of assistive devices. Understanding the relationship between BMI, thigh length difference, and knee angle during stair climbing can help clinicians better assess and manage gait abnormalities in individuals navigating stairs.

Key Words:
Body mass index, Knee angle, Stair ambulation, Healthy young adults, Kinovea® software.

Introduction

The ability to engage in stair climbing is influenced by various factors associated with aging, such as declines in muscle strength, balance, visual acuity, cognitive function, and the presence of lower extremity pain[1,2]. Consequently, stair-related falls are common during ascending and descending stairs, often resulting in significant injuries. Stairs contribute approximately 27% of all fall-related traumatic brain injuries among young and middle-aged adults[3]. Given these risks, the attention of healthy young adults is particularly warranted when using stairs.

Notably, individuals with obesity exhibit distinct compensatory behaviors, such as hesitation, reliance on handrails, and utilizing step-by-step strategies during stair ascent and descent, compared to individuals who are overweight or of normal weight[4]. Moreover, individuals with diabetic peripheral neuropathy, independent of diabetes itself, experience less stable center-of-mass displacements while ascending and descending stairs compared to their healthy counterparts[5]. Similarly, individuals with knee pain, particularly those with patellofemoral knee pain, demonstrate

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larger foot contact areas and lower peak pressure amplitudes during stair descent than those without knee pain. Scholars[6] indicate that individual and environmental factors frequently influence the risks of ascending and descending stairs.

Ascending and descending stairs are common activities in everyday life, significantly contributing to daily physical exertion, as they require 8-10 times more energy than resting[7,8]. Regular stair climbing has numerous health benefits, including improved aerobic capacity, fitness, and body composition[9-11]. Stair climbing holds great appeal for the general public due to its potential positive impact on overall health and well-being. In recognition of its value, interventions promoting stair use have been implemented in various settings, particularly workplaces, demonstrating their effectiveness in encouraging physical activity[12-14]. However, it should be noted that these interventions have primarily targeted office workers and young adults, warranting the need for a broader understanding of stair-climbing patterns across different populations[15].

Stair climbing imposes a higher load on the knee joint than walking, making it an activity of particular interest in biomechanical studies[16]. Previous research by Guo et al[17] revealed that ascending stairs with a toe-out (TO) gait leads to an increase in the first peak knee adduction moment (KAM) while decreasing the second peak KAM[17]. Conversely, Bennett et al[18] found that a toe-in (TI) gait reduces the first peak KAM without an increase in the second peak KAM, and it also decreases the knee adduction angular impulse (KAAI)[18]. This suggests that toe-in (TI) gait may be more advantageous than toe-out (TO) for stair ascent. Conversely, there is minimal difference in knee adduction moment (KAM) during stair descent between a normal foot progression angle (FPA) and TO gait. Furthermore, TI gait is more effective than usual, and TO gaits reduce KAM and KAAI during stair descent[19]. Additionally, stair descent alters head coordination, resulting in increased sagittal head and neck excursions and more synchronized in-phase coordination with the trunk than stair ascent or level walking[20].

Kinematics research is vital in objectively analyzing human movement across various disciplines, such as sports management analysis, clinical research, footwear, and orthopedic[21]. It enables the collection of quantifiable data and facilitates comparisons between different subjects or time points, including pre- and post-treatment or training[21]. While three-dimensional motion analysis systems are considered the gold standard for evaluating gait, they have inherent limitations, including high equipment costs, the need for trained personnel, lengthy processing times, and large installation spaces[22]. However, recent advancements have introduced low-cost 2D technologies that offer comparable precision to high-end reference systems[23]. One such accessible tool is Kinovea.

Kinovea is a simple, portable, and freely available software that facilitates field-based kinematic measurements without prior expertise, ensuring accurate and reliable data acquisition[24]. It has found extensive application in three major domains: sports research[25-28], clinical analysis[29,30], and as a tool for comparing the reliability of novel technologies[31]. Previous investigations[21] have examined the inter-rater reliability of Kinovea® in detecting the initial contact phase during running, demonstrating a clear correlation (kappa = 0.76-0.92). Furthermore, Damsted et al[32] evaluated the reliability of Kinovea software, revealing more excellent intra-rater agreement (kappa = 0.83-0.88) compared to the inter-rater agreement (kappa = 0.50-0.63). Additionally, Kinovea has been validated to evaluate time-related variables[24].

First, this study examines how young, healthy adults experience different knee angles when ascending stairs using a simple, portable, and freely available tool. With a special emphasis on the kinematics of the knee joint, this goal aims to shed light on the biomechanical aspects of stair climbing. The study also aims to comprehend the variations in knee angles between stair climbing and stair descending. Through an analysis of these variations, the study seeks to clarify how people modify their gait during various stages of stair climbing, providing insight into biomechanical adjustments made in response to changing task requirements. Finally, the study intends to investigate how knee angles during stair ascent and descent are impacted by body mass index (BMI). This objective aims to ascertain whether BMI, a measure of body composition, significantly influences knee angle patterns during stair ambulation.

Patients and Methods

Participants

Forty-three healthy male participants from Prince Sattam bin Abdulaziz University, aged between 19 and 25 years (mean age = 22.9 years,

SD = 1.4 years), were recruited for this study. The study's internal validity was enhanced by maintaining a more uniform participant group through the restriction of the sample to one gender. Additionally, young adults are a demographic that is well-suited for researching baseline gait patterns and biomechanical adaptations during stair climbing because they represent a time when musculoskeletal development and function are relatively stable. Participants with a history of knee surgery, chronic knee pain, neurological disorders, or balance problems were excluded from the study. The preferred leg for stair ascent was determined according to Peter's criteria (1988), resulting in 19 participants (64.5%) preferring the right leg. Ethical approval for the study was obtained from the Prince Sattam bin Abdulaziz University ethical committee (No.: RHPT/020/057), and all participants provided written informed consent.

Experimental Setup

The experimental staircase consisted of five steps with a total length of 2.15 m. Each step had a height of 10 cm, a tread length of 32 cm, and a tread width of 58 cm (Figure 1). Videos were recorded using a Canon EOS 90D (Canon Inc., Tokyo, Japan) digital camera with a resolution of 1,280 x 720 pixels at 50 frames per second (fps). The camera was positioned on a tripod at 2.5 m and 1.15 m above the floor, perpendicular to the staircase.

To establish a spatial scale, reference objects with known dimensions had to be captured within the camera's field of view during calibration. A measurement bed with known dimensions was specifically positioned within the camera's field of view to determine pixel-to-distance conversion factors. Furthermore, to guarantee consistent start and finish points for data analysis, a start mark on the floor and an end mark on the fifth step were placed precisely to indicate the start and finish of stair ascents and descents.

Furthermore, Kinovea® version 0.9.3 (www.kinovea.org), an open-source, reliable, and valid low-cost motion capture software for analyzing kinematics data was utilized for video analysis. Height (cm) and weight (kg) measurements were obtained using a Weight Beam Eye-Level scale (Detecto, Webb City, MO, USA).

Data Collection

Data collection occurred at the Biomechanics Laboratory in the Health and Rehabilitation Sciences Department at the College of Applied Medical Sciences, Prince Sattam bin Abdulaziz University. Anthropometric measures of participants, including bilateral leg length, height, and weight, were recorded to calculate hip, knee, and ankle joint angles. Thigh length was determined by measuring the distance between the greater trochanter and the lateral condyle of the femur, and tibia length was determined by measuring the distance between the tibial tuberosity and the external malleolus. Three reflective markers (38 x 21.2 mm) were placed in selected anatomical positions in the lower limb, following the model of Kadaba et al[33]. To ensure uniformity and reduce measurement variability, the same skilled examiner collected the anthropometric data.

Test Procedure

Practice trials were given to participants to ensure they understood the task and to help them get used to the experimental setup. Participants in these practice trials were given guidance throughout the stair-climbing task and were free to move at a comfortable pace they chose. During these practice trials, the researchers gave the participants feedback on their performance and clarified any parts of the task instructions that needed clarification. Participants were instructed to stand on a designated mark on the floor (start mark), one meter from the staircase. They were then asked to ascend the five-step staircase at their self-selected comfortable pace, placing only one foot on each

Figure 1. The experimental setup, which includes a staircase, a camera mounted on a tripod, a weight beam eye-level scale, a measurement bed, a start mark on the floor, and an end mark on the fifth step.

step. An end mark was placed on the fifth step to mark the completion of the first ascent and the first video recording. Participants were instructed to descend and return to the start mark to complete the first descent. Each participant completed two ascents and two descents, resulting in four video recordings.

Data Processing and Analysis

Stair climbing was divided into two phases: the ascent phase and the descent phase. In the ascent phase, a stride cycle was defined as the first foot contact on the ground and ended at the same foot contact on the fifth step. In the descent phase, the stride cycle was defined as the first foot contact on the fifth step and the same foot contact on the ground. The video recordings were displayed and processed using Kinovea® software, and the knee angles were calculated using the angle function. The exported data were processed and filtered using Microsoft Excel (Microsoft Corp., Redmond, WA, USA) and analyzed in IBM SPSS statistics version 26 (IBM Corp., Armonk, NY, USA). The main variables analyzed were cycle duration, stride phase, velocity, and hip and knee angles during stair climbing. Data were presented as mean and standard deviation (SD) for angles and velocity. The mean maximum flexion/extension angles were calculated based on an average of two trials for each participant. Furthermore, the thigh length difference was calculated as the absolute difference between the length of the right and left thighs for each participant. This analysis aimed to investigate whether there was a correlation between knee angle during stair climbing and the magnitude of thigh length difference and to explore potential biomechanical factors that might influence knee angle variations during stair ambulation.

Table I. Demographic characteristics of participants.

Demographics	Mean ± SD
Age (years)	22.9 ± 1.4
Height (m)	1.7 ± 0.1
Weight (kg)	79.9 ± 20.7
BMI (kg/m^2)	26.6 ± 7.0
Right thigh length (cm)	46.1 ± 5.4
Left thigh length (cm)	45.9 ± 5.3

Data is expressed in mean ± standard deviation; m, meter; kg, kilogram; cm, centimeter; BMI, body mass index.

Statistical Analysis

Statistical analyses were carried out to determine the significance of any observed differences between conditions or groups. A one-way analysis of variance (ANOVA) was specifically used to compare variables such as cycle duration, stride phase, and velocity between different conditions (e.g., right *vs.* left leg dominance, ascent *vs.* descent). Pairwise comparisons were carried out using post-hoc tests, such as Tukey's Honestly Significant Difference (HSD) test, if significant differences were found. Furthermore, the relationship between knee angle and thigh length difference during ascending and descending stairs was examined using Pearson correlation coefficients in correlation analyses. Each statistical test was carried out with a significance set at $p < 0.05$. The analyses were performed using IBM SPSS statistics version 26 (IBM Corp., Armonk, NY, USA).

Results

The study consisted of 43 healthy male participants from Prince Sattam bin Abdulaziz University. The participants ranged from 19 to 25 years, with a mean age of 22.9 years (SD = 1.4 years). Their height ranged from 1.6 m to 1.9 m, with a mean height of 1.7 m (SD = 0.1 m). The participants' weight ranged from 51 kg to 149.5 kg, with a mean weight of 79.9 kg (SD = 20.7 kg). Their BMI ranged from 17.2 kg/m² to 54.3 kg/m², with a mean BMI of 26.6 kg/m² (SD = 7.0 kg/m²). The majority of participants fell into the overweight category (n = 24), followed by those in the ideal weight category (n = 15), and a smaller number in the obese category (n = 4).

Regarding leg preference during stair climbing, 27 participants (62.8%) preferred using their right leg for ascending the stairs, while the remaining 16 participants (37.2%) preferred their left leg. The thigh lengths of the participants varied, with the right thigh length ranging from 38.5 cm to 57.0 cm and the left thigh length ranging from 38.0 cm to 57.5 cm. The average thigh length across participants was 45.2 cm (SD = 6.2 cm).

Participants' ascending time ranged from 5.0 to 8.0 seconds, and descending time ranged from 4.0 to 7.0 seconds. The swing phase during stair climbing ranged from 0% to 40%, and the stance phase ranged from 40% to 60%. Table I displays the demographic characteristics of the sample, including the mean values and standard deviations.

Influence of Body Mass Index (BMI) on Knee Angle during Stair Climbing

A one-way analysis of variance (ANOVA) was conducted to examine the influence of BMI on the knee angle during ascending and descending stairs. The results revealed that the effect of BMI was not statistically significant on the knee angle in ascending stairs [F (2, 40) = 0.75, $p = 0.47$] and in descending stairs [F (2, 40) = 0.58, $p = 0.56$].

Table II provides an overview of the mean and standard deviation of the knee angle during ascending and descending stairs for different BMI groups.

Gait Parameters Analysis during Stair Climbing

The results of the inferential statistical tests indicated significant differences in the gait parameters during stair climbing (Table III). A *t*-test comparing the cycle duration between ascending and descending stairs revealed a significant difference [t (42) = 2.36, $p < 0.05$], with participants demonstrating shorter cycle duration during ascending stairs (M = 4.52 s, SD = 0.76 s) compared to descending stairs (M = 4.72 s, SD = 0.81 s).

Regarding the stride phase, the analysis of variance (ANOVA) showed a significant main effect of BMI categories [F (2, 40) = 3.82, $p < 0.05$]. Post-hoc comparisons using Tukey's HSD test revealed significant differences in stride phase between the ideal weight and overweight categories ($p = 0.036$) and between the ideal and obese categories ($p = 0.022$). However, no significant difference was found between the overweight and obese categories. The mean stride phase for the different BMI categories was as follows: ideal weight (M = 47.12%, SD = 3.21%), overweight (M = 48.02%, SD = 2.87%), and obese (M = 48.96%, SD = 2.87%).

In terms of velocity, a significant main effect of stair direction was observed. Participants displayed a higher velocity during ascending stairs (M = 1.23 m/s, SD = 0.18 m/s) compared to descending stairs (M = 1.19 m/s, SD = 0.21 m/s), as determined by a paired *t*-test (t (42) = 2.19, $p < 0.05$).

These findings indicate that stair direction and BMI categories impact gait parameters during stair climbing. Participants exhibited faster cycle duration and higher velocity during ascending stairs, suggesting a more dynamic movement pattern. Additionally, individuals in the ideal weight category displayed a slightly different stride phase compared to those who were overweight or obese.

Association Between Knee Angle and Thigh Length Difference

A correlation analysis was conducted to explore further the relationship between knee angle and thigh length difference. The Pearson correlation coefficient was calculated to assess the strength and direction of the relationship between

Table II. Knee angle during ascending and descending stairs for different BMI groups.

Condition	Ideal weight	Overweight	Obese	*p*-value
Ascending stairs	64.3 ± 7.6	66.4 ± 6.0	63.2 ± 6.1	0.47
Descending stairs	64.9 ± 6.1	65.0 ± 6.3	62.3 ± 7.6	0.56

Data are expressed in mean ± standard deviation in degrees.

Table III. Gait parameters during stair climbing.

Variable	Comparison	Mean ± SD	*p*-value
Cycle duration (s)	Ascending *vs.* descending	4.52 ± 0.76	< 0.05
Stride phase (%)	BMI categories		
	Ideal weight *vs.* overweight	47.12 ± 3.21	0.036
	Ideal weight *vs.* obese	45.78 ± 3.61	0.022
	Overweight *vs.* obese	48.96±2.87	0.046
Velocity (m/s)	Ascending stairs	1.23 ± 0.18	< 0.05
	Descending stairs	1.19 ± 0.21	< 0.05

Data is expressed in mean ± standard deviation; s, seconds; m, meter; BMI, body mass index.

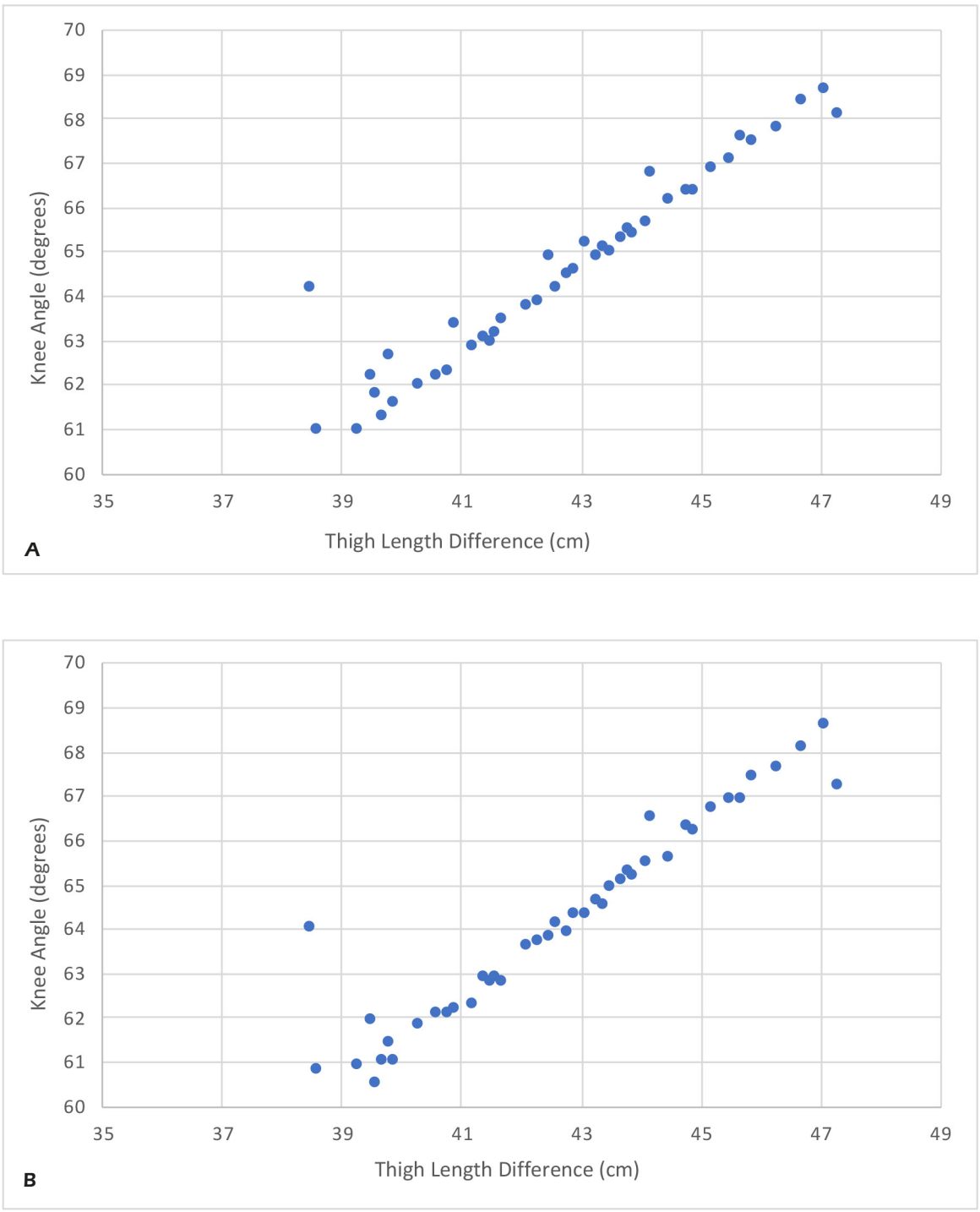

Figure 2. Scatter plot depicting the relationship between knee angle and thigh length difference during (**A**) ascending and (**B**) descending stairs.

these variables during ascending and descending stairs. The analysis aimed to determine whether participants with more significant thigh length differences exhibited larger knee angles.

The results of the correlation analysis revealed a significant relationship between knee angle and thigh length difference during ascending and descending stairs. For ascending stairs, a positive

correlation was found between knee angle and thigh length difference ($r = 0.42$, $p < 0.05$), indicating that participants with more significant thigh length differences exhibited larger knee angles. Similarly, during descending stairs, a significant positive correlation was observed between knee angle and thigh length difference ($r = 0.38$, $p < 0.05$), suggesting that participants with more significant thigh length difference had increased knee angles.

A scatter plot was generated to visually illustrate the relationship between knee angle and thigh length difference (Figure 2). The x-axis represents the thigh length difference, while the y-axis represents the knee angle. Each data point in the scatter plot represents an individual participant. The plot demonstrates the positive relationship between knee angle and thigh length difference during ascending and descending stairs, with participants exhibiting more significant thigh length difference tending to larger knee angles.

Discussion

The present study investigated the influence of BMI, thigh length difference, and knee angles on gait parameters during stair climbing. The findings provide valuable insights into the relationship between these factors and shed light on the biomechanical adaptations during this locomotor task. In comparing the results of this study with previous research[15,16], similarities and differences emerge, indicating the complex nature of gait dynamics during stair climbing. Differences in methodology could be one cause of the discrepancies between the current study and earlier research[4]. Studies examining the connection between knee angles and BMI while climbing stairs may use various procedures for gathering and processing data. Divergent results, for instance, could result from variations in the number of steps in the experimental staircase, the locations of the cameras used for video recording, or the kinematic analysis software (Kinovea® in this study). The participants' characteristics also greatly impact how studies turn out. The present investigation was limited to healthy young adult males, which may have limited the findings' applicability to other demographics.

Consistent with previous studies[34], this study's findings revealed significant differences in gait parameters between ascending and descending stairs. Participants exhibited shorter cycle durations during ascending stairs, indicating a faster gait pattern in response to the task demands. This finding aligns with adapting gait patterns to different stair directions[35-36]. Similarly, the higher velocity observed during ascending stairs aligns with previous research[37] reporting increased dynamic movement patterns during this phase.

Regarding the influence of BMI on gait parameters, the results of this study showed a significant effect on the stride phase. Participants in the obese category demonstrated a different stride phase than those in the ideal weight and overweight categories. These findings are consistent with previous studies that have reported altered gait patterns in individuals with higher BMI[38,39]. However, in contrast to some studies[40], no significant effect of BMI on knee angles during stair climbing was observed in this study. This discrepancy may be attributed to differences in sample characteristics, measurement techniques, or stair-climbing protocols across studies.

The correlation analysis revealed a positive relationship between knee angles and thigh length difference during ascending and descending stairs. This finding aligns with previous research indicating the impact of limb length discrepancy on joint kinematics[41,42]. The positive correlation suggests that participants with more significant thigh length differences tend to exhibit larger knee angles. This highlights the potential influence of thigh length asymmetry on knee joint biomechanics during stair climbing.

The study's results have important implications for interventions and clinical practice that address gait abnormalities and injury prevention, especially when it comes to stair climbing. Through the identification of correlations between knee angles, thigh length difference, and BMI during stair walking, medical practitioners can create customized rehabilitation plans that effectively address biomechanical issues. These regimens could incorporate specific exercises to enhance muscle coordination, strength, and flexibility, as well as gait retraining methods to encourage healthy alignment and movement patterns. Furthermore, the results guide the creation of focused interventions to optimize gait parameters and lower the risk of falls during stair ascent and descent for high-risk groups, such as elderly adults or people with musculoskeletal disorders. Insights gained from this research can also inform the development of accessibility adjustments and assistive technology for people with irregular gait or limited mobility, improving their safety and independence when navigating stairs.

The research highlights the significance of customized strategies and focused interventions for enhancing gait biomechanics and reducing the likelihood of injuries caused by stairs in various demographic settings.

It is important to note that this study has some limitations. The sample size was relatively small, which may limit the generalizability of the findings. Future research with more extensive and diverse samples must validate and expand upon these results. Additionally, the study focused exclusively on healthy male participants, and therefore, caution should be exercised when extrapolating the findings to other populations or genders. Further investigations involving different demographic groups would enhance the comprehensiveness and applicability of the research.

Conclusions

This study used Kinovea® software to measure the variables objectively while measuring the BMI, thigh length difference, and knee angles during stair climbing in young, healthy adults. While gait parameters like cycle duration, stride phase, and velocity varied between ascending and descending stairs, BMI had no discernible effect on knee angles during stair ambulation. Significantly, a positive correlation was discovered between knee angle and thigh length difference, indicating that people with larger thigh length differences might have larger knee angles when climbing stairs.

These results highlight the intricacy of biomechanical adjustments made during stair climbing and provide an understanding of how gait dynamics change in response to different task requirements. Comprehending these correlations is imperative for developing assistive devices intended to mitigate abnormalities in gait and lower the risk of injury during stair negotiation, as well as for clinical practice and rehabilitation programs.

Future studies could examine other elements like proprioceptive feedback, joint stability, and muscle strength that affect gait adaptations during stair climbing. Studies that track gait patterns over extended periods and among diverse populations may offer additional perspectives on the development of biomechanical modifications and help design tailored interventions. Furthermore, studies examining the effectiveness of specific interventions, like gait training plans or orthotic devices, in enhancing the mechanics of climbing stairs could improve clinical management approaches.

This study advances our knowledge of the biomechanics of stair climbing and emphasizes the significance of considering individual traits when diagnosing and treating gait abnormalities. Understanding the fundamental processes of stair ambulation will help us create more successful interventions to promote safe and effective stair negotiation in a variety of demographic settings.

Conflict of Interest

The authors declare that they have no conflict of interest.

Informed Consent

All participants provided written informed consent before participating in the study. They were briefed on the purpose, procedures, and potential risks and benefits of the study, and their voluntary participation was emphasized. Participants were assured of confidentiality and their right to withdraw from the study at any time without consequence.

Ethics Approval

The Prince Sattam bin Abdulaziz University Ethical Committee granted ethical approval for the study under the reference number RHPT/020/057.

Acknowledgments

The authors thank all the participants in this study and acknowledge the support of the Prince Sattam bin Abdulaziz University Biomechanics Laboratory, which provided facilities for data collection.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Funding

This study is supported by funding from Prince Sattam bin Abdulaziz University's project number (PSAU/2024/R/1445).

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