Gait & Posture 113 (2024) 337–344

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Effects of overweight and obesity on lower limb walking characteristics from joint kinematics to muscle activations

Malek Adouni [a,b,*], Fadi Alkhatib [c], Raouf Hajji [d], Tanvir R. Faisal [e]

[a] Biomedical and Instrumentation Engineering Program, Abdullah Al Salem University, Khalidiya, Kuwait
[b] Department of Physical Medicine and Rehabilitation, Northwestern University, 345 East Superior Street, Chicago, IL 60611, USA
[c] Department of Mechanical Engineering, Australian University, P.O. Box 1411, East Mushrif, Kuwait
[d] Medicine Faculty of Sousse, Department of Internal Medicine, Sidi Bouzid Hospital, University of Sousse, Tunisia
[e] Department of Mechanical Engineering, University of Louisiana at Lafayette, LA 70508, USA

ARTICLE INFO

Keywords:
Obesity
Kinetics
Kinematics
Gait
Osteoarthritis

ABSTRACT

Background: Obesity is a crucial factor that increases the risk of initiating and advancing knee osteoarthritis. However, it remains unclear how obesity directly impacts the biomechanical experience of the lower limb joints, potentially triggering or exacerbating joint degeneration. This study investigated the interactive effects of BMI augmentation on lower limb kinematics, kinetics, and muscle activations during walking.
Methodology: A group of 60 participants underwent a three-dimensional gait analysis. These individuals were categorized into three groups based on their body mass index (BMI): those with a BMI below 25 were classified as having a healthy weight, those with a BMI between 25 and 30 were categorized as overweight, and those with a BMI exceeding 30 were considered obese. This study analyzed the gait of 60 participants categorized by BMI. During walking trials, they recorded ground reaction forces electromyography of leg muscles like the gastrocnemii, hamstrings, and quadriceps. Lower limb joint angles and net moments were also calculated. Statistical mapping identified variations in kinematic, kinetic, and muscle activation patterns across the stance phase between BMI groups.
Results: The results displayed distinct biomechanical patterns in obese individuals. Notably, there was a significant increase in flexion observed in the hip and knee joints ($P < 0.001$) during the initial stance phase and an increase in hip and knee adduction angles and moments throughout the entire stance phase ($P < 0.001$). Additionally, muscle activations underwent significant changes ($P < 0.01$), with a positive correlation noted with the BMI factor. This correlation was most pronounced during the early stance phase for the quadriceps and hamstring muscles and the late stance phase for the gastrocnemius.
Conclusion: These findings represent a comprehensive picture that contributes to understanding how excess weight and obesity influence joint biomechanics, highlighting the associated risk of joint osteoarthritis.

1. Introduction

Diabetes, heart disease, and the progression of osteoarthritis in the knee have all been linked to obesity [1]. Knee osteoarthritis, in particular, is explained by the added stress that excess weight places on the joints, increasing the rate of cartilage degeneration[2]. In the U.S., from 1966 to 2018, the prevalence of obesity among adults drastically rose from 13.4 % to 42.7 %, indicating that over two in five adults are now categorized as obese[3]. Studies on disabled adults also found that the leading causes of disability are osteoarthritis and rheumatism. As obesity has rapidly spread through today's society, its consequences are becoming more significant [4]. It is theorized that the rising rates of obesity will likely speed up related conditions like knee osteoarthritis. Knee osteoarthritis is highly relevant to current research. Therefore, it is important to understand how excess weight and obesity affect risk factors associated with joint osteoarthritis.

Over the past three decades, significant research has investigated the complex relationship between osteoarthritis and walking biomechanics. People with knee osteoarthritis display unique biomechanical patterns compared to healthy individuals [5–12]. These patterns include decreased knee flexion range, lowered highest flexion angle, reduced peak external flexion moments, increased peak adduction angles during

* Correspondence to: Abdullah Al Salem University, biomedical and instrumentation engineering, Khalidiya, Kuwait.
E-mail address: malek.adouni@gmail.com (M. Adouni).

https://doi.org/10.1016/j.gaitpost.2024.06.024
Received 12 January 2024; Received in revised form 16 May 2024; Accepted 26 June 2024
Available online 28 June 2024

the stance phase, and higher peak external adduction moments [8, 13–16]. A key factor linking obesity to osteoarthritis is the convergence in biomechanical effects [17]. Obese people, unlike individuals of normal weight, exhibit greater peak knee adduction angles during walking. Extensive research has mapped out the distinct gait patterns of those with knee osteoarthritis and highlighted how obesity can influence joint biomechanics through mechanisms like increased adduction angles during gait [11,18,19].

Other research has found that obese individuals tend to exhibit decreased knee flexion during early stances as well [20–23]. However, it is important to note that research findings have sometimes contradicted one another [24–26]. This uncertainty arises from several sources, including studies on the association between obesity and osteoarthritis that were not sufficiently validated, which may have inadvertently included obese individuals in the early stages of the disease [27]. Furthermore, Knee Adduction Moments [KAM], which involve the strength and the duration of the KAM, are significantly greater in individuals with knee OA, showing increased stress on the knee joint during walking [28]. Obese individuals have substantially greater ef degrees of inward knee motion in both the standing and swinging phases of walking.

Additionally, the outward tilting of ankles is usually exhibited by obese individuals from mid-stance to pre-swing, and the maximum force exerted by the muscles pulling the foot downward decreases. In contrast, the increased force tilting the ankle [29] plays an important role in knee joint loading while walking, and current studies have focused on lower limb muscle strength in knee OA individuals. Weakening of the quadriceps muscles is observed among knee OA individuals. Hamstring muscle strength has received less focus; therefore, findings contradict [28].

[29]. Considering these overlooked aspects, a comprehensive view is crucial for gaining deeper insights into how obesity impacts joint biomechanics - an area that most previous investigations have largely overlooked. This holistic perspective provides a valuable tool.

Consequently, the study aimed to quantify and investigate patterns of lower limb kinematics, kinetics, and muscle activations during overground walking tasks in healthy and unhealthy-weight individuals. The intention was to fill a vacuum in the literature by offering a thorough knowledge of lower limb biomechanics. It was predicted that there would be significant differences in lower limb kinematic and kinetic patterns and muscle activation between healthy-weight and unhealthy-weight people, ultimately resulting in increased joint strain. Three groups were classified according to differences in Body Mass Index (BMI) to accomplish this research goal, and gait analysis was performed.

2. Methods

2.1. Study design

This study employed a quantitative, comparative research design to analyze lower limb biomechanics across different BMI categories.

2.2. Study setting

The study was conducted in Kuwait between 2020 and 2022 at the Australian University Scientific Research Centre, biomechanics and biomodeling unit, in collaboration with the Physical Medicine W Hospital.

2.2.1. Eligibility criteria

2.2.1.1. Inclusion criteria.

- Subjects were included if they were male between 18 and 30 years old.
- Subjects were included if they had a stable body weight with less than a 2.5 kg change in the previous three months.
- Subjects were included if they participated in less than 30 minutes of moderate physical activity 3 days per week.
- Subjects were included if they had no history of knee pain or lower limb surgery.
- Subjects were included if they provided informed consent to participate in the study.

2.2.1.2. Exclusion criteria.

- Subjects were excluded if they had a history of knee pain or previous lower limb surgeries.
- Subjects were excluded if they participated in more than 30 minutes of moderate physical activity 3 days per week.
- Subjects were excluded if they had a change in body weight greater than 2.5 kg in the previous three months.
- Subjects were excluded if X-ray images of their knee joints showed any signs of osteoarthritis.

2.3. Subject population

The research study recruited 60 individuals (male) who were matched in terms of age, daily activity level, and stable body mass (Table 1) (with less than a 2.5 kg change in the previous three months). These individuals had never experienced knee pain or undergone lower limb surgery. The participants were sourced through university announcements and advertisements. Before conducting the tests, all subjects provided informed consent following the institutional ethics review board guidelines.

2.4. Data collection

They were then divided into three groups of 20 individuals based on BMI according to the WHO guidelines (Table 1). The first group included individuals with a BMI below 25, classified as having a healthy weight. The second group was categorized as overweight and consisted of individuals with a BMI between 25 and 30. while the last group, classified as obese, comprised individuals with a BMI exceeding 30 [30]. Every participant was fully upright when X-ray images of their knee joint were captured in the frontal and sagittal planes. This was achieved using the Digital Diagnost Rel 4.3 X-ray equipment from Philips Medical Systems. The X-ray images were then carefully reviewed by both a rheumatologist and an orthopedist to ensure that there was no observed association between osteoarthritis and obesity in the subjects.

Table 1
Demographics of Healthy weight, Overweight, and Obese subjects.

	Healthy weight	Overweight	Obese
Age (years)	32.65 (3.93)	34.22 (5.27)	31.81 (5.34)
Height (m)	1.78 (0.021)	1.76 (0.028)	1.73 (0.025)
Mass (kg)	74.51 (5.29)	85.23 (4.89)	97.62 (5.03)
BMI (kg/m2)	21.78 (1.65)	27.57 (1.32)	32.87 (1.88)

2.5. Gait analysis

This study used the synchronized P6000 force platform (BTS-Bioengineering, Inc.) and an optoelectronic motion capture system to measure the external ground reaction forces and 3D motion of the lower limb for all participants. The motion capture system consisted of eight cameras (SMART-DX EVO, BTS-Bioengineering, Inc.) with a sampling frequency of 100 Hz. Twenty-two spherical reflective markers, each with a diameter of 20 mm, were positioned on specific anatomical landmarks, acromion, ASIS, sacrum, greater trochanter, femoral condyle, fibula head, lateral malleolus, fifth metatarsal head, and heel. Additional bar markers were placed on the shank and thigh segments [31–33]. These and virtual markers identified during quiet standing were used to establish anatomical coordinate systems for lower limb segments [34,35]. To collect data, participants were required to walk barefoot at a self-determined pace for at least five walking trials per person. The barefoot strategy was preferred to standardize and control the variability caused by different kinds of footwear. It allows for a more natural walk and promotes more accurate data on how obesity impacts lower limb kinematics. Additionally, unchanged ground response forces and marker coordinates had 15 Hz and 6 Hz cut-off frequencies, respectively [36]. This method allows us to effectively distinguish and evaluate the biological process of knee movements and muscle activations, suggesting a better understanding of the effects of obesity on walking kinetics.

The lower limb extremity's kinematics and kinetics were assessed using the segments connecting the hip and knee joint centers, knee and ankle joint centers, and ankle-to-toe joint centers as rigid entities [37]. The angular and translational positions of each segment were computed using the traditional inverse kinematic technique, where a least-squares optimization algorithm aimed to minimize the disparity between the position of each rigid body and the measured marker data [37] Calculating a hip joint center in individuals with obesity is challenging due to inaccuracies in anatomical marker placement (especially GT and right/left Anterior superior iliac spine). To address this, tactile and operational measurement techniques were applied to assess the greater trochanter and ASIS in obese individuals correctly. Palpation can be challenging due to the presence of soft tissue. To identify GT, participants lie on their sides to make GT prominent, with weight shifted to the opposite leg. Tactile methods involved touching or palpating with fingertips or hands to identify the anatomical landmarks. Operational measurements involve individuals actively calculating the hip joint center. Participants were requested to perform hip abduction and rotation to help identify GT, which can be seen gliding under the skin. To identify ASIS, participants must be in a standing position or lie down to make ASIS more apparent. Palpation was performed from the waistline and moved downwards, checking for the protruded bony structure of the ASIS. Operational methods involve asking the participants to raise their knees towards their chest while lying down. This movement makes ASIS more visible. One hand can examine the ASIS with the thumb, while the other hand can help hold the pelvis. The safest body markers were used to locate the areas to minimize the disparity between the position of each rigid body and the measured marker data.

Employing an inverse dynamics approach, the net external moments acting on the lower limb joints were calculated based on the inertial properties of the limb segments [38], measured ground reaction, and predicted three-dimensional motion data. The angles and moments at each joint were described using the anatomically derived joint coordinate system defined by Grood and Suntay [39]. Various stride properties were also calculated, including stance time and percentage, walking speed, and stride length. The gait cycle is the time that passes between a foot's first and second ground contacts [40]. All computations were performed using customized algorithms in Matlab (The Mathworks, Natick, MA, USA).

The experiments used surface electromyography (FREEEMG) preamplifiers from BTS-Bioengineering, Inc. to capture muscle activities simultaneously. These preamplifiers were placed over seven muscles in the lower limbs, namely rectus femoris, vastus medialis and lateralis, lateral hamstrings (biceps femoris), medial hamstrings (semimembranosus), lateral gastrocnemius, and medial gastrocnemius. The muscles were identified by palpating bony landmarks and observing active contractions [41]. The methodology described by Besier et al. was followed in processing the recorded activities [36].

To examine the disparities in discrete temporal-distance gait variables, we employed unpaired t-tests and the Mann-Whitney U Test according to the normality characteristics of the distribution. Furthermore, we employed one-dimensional statistical parametric mapping to gain deeper insights into potential variations in kinematics, kinetics, and muscle activation variables across the entire stance cycle within the three BMI categories [42]. For all comparisons, $p<0.05$ was set as the significance level.

3. Results

Differences in stride characteristics were evident between the obese participants and the rest of the participants (including the healthy weight and overweight groups), as indicated in Fig. 1. Obese participants exhibited a 20 % longer stride time ($p<0.001$), a 16 % lower average velocity ($p<0.002$), and an 8 % decrease in cadence distribution ($p<0.01$) compared to the healthy weight group, all at their self-selected speed **(**Fig. 1**)**. However, the disparities were less pronounced when examining other temporal parameters, with the obese participants showing slightly longer stance and support phases. Concerning spatial parameters, the obese participants had a 7 % shorter stride length and a 13 % wider step width ($p<0.01$). Comparing these parameters between the healthy weight and overweight participants revealed fewer noticeable differences, except for the mean velocity and stride length, where a significant decrease was observed in the overweight group ($p<0.02$) (Fig. 1).

The stride characteristics underwent a significant transformation, revealing distinct disparities in joint angles between healthy/overweight individuals and those who were obese **(**Fig. 2**)**. Obese participants displayed a notable increase in hip flexion during the initial stance phase (<18 %) ($p<0.012$), followed by a marked increase in hip extension during the later stance phase (>60 %). At the same time, insignificant differences were observed during the intermediate stages when compared to individuals of healthy weight **(**Fig. 2**)**. Throughout the stance phase, the obese participants exhibited substantially higher hip adduction and external rotation levels in both the frontal and transversal planes ($P<0.001$). Likewise, when focusing on the knee joint, the obese participants exhibited a decreased flexion angle ($P<0.01$), heightened adduction ($P<0.001$), and internal rotation ($p<0.001$) during the stance phase (Fig. 2). Simultaneously, the ankle joint displayed increased dorsiflexion and internal rotation, with an almost equal average augmentation of 13 % ($P<0.001$). Noteworthy differences in ankle inversion and eversion rotations were observed during the early and late stance phases (>22 % and <77 % of the stance phase), further emphasizing the distinctions between the two groups **(**Fig. 2**)**.

The changes in joint moments closely resembled the alterations in joint rotations **(**Fig. 3**)**. When comparing obese participants to those with a healthy weight, it was observed that they initially walked with a notably higher hip flexor moment, which then transitioned to a higher extensor moment during the latter half of the stance phase. Throughout the entire stance phase of gait, the obese group exhibited significantly higher adduction and external reaction moments **(**Fig. 3**)**. The knee joints of obese individuals displayed considerably greater flexion, adduction, and internal moments, with the maximum differences being 0.21 Nm/kg, 0.28 Nm/kg, and 0.14 Nm/kg, respectively **(**Fig. 3**)**. Regarding the ankle, minimal differences were detected among all participants in the joint moment within the frontal plane. However, obese participants demonstrated higher dorsiflexion and internal moment during the late stance phase **(**Fig. 3**)**. Most of the computed

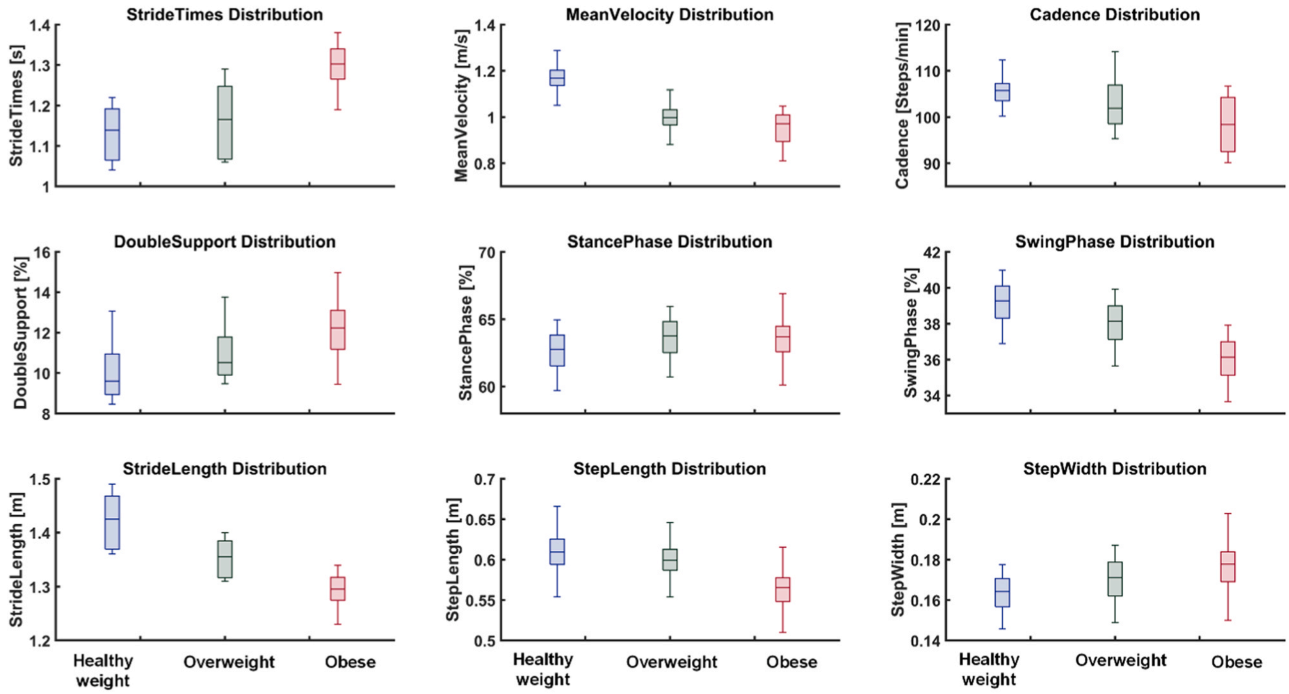

Fig. 1. Stride characteristics of healthy weight, overweight, and obese subject groups.

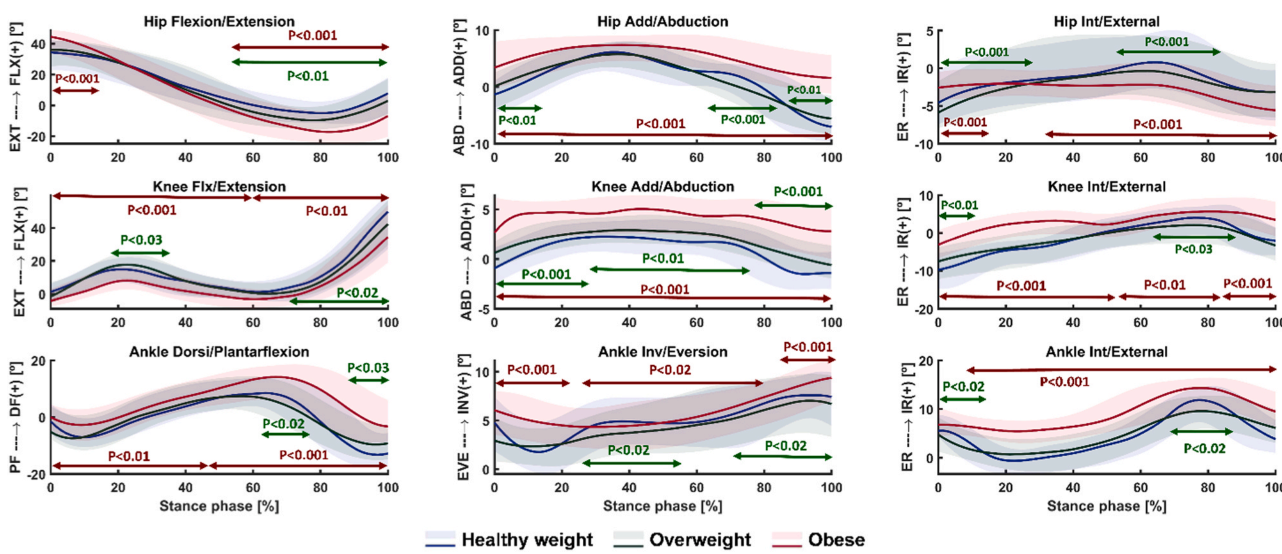

Fig. 2. Lower extremity joint rotations for the Healthy weight, Overweight, and Obese participants, with region statistical significance, indicated for Obese Vs Healthy weight (◄—►) and Overweight Vs. Healthy weight (◄—►).

reaction moments in the lower limb did not exhibit noticeable disparities between the healthy and overweight groups compared to the obese group. These differences followed a similar trend of moment augmentation observed in the obese group. As expected, all participant groups experienced significant increases in ground reaction forces, particularly in the vertical component (Fig. 4), with a peak increase of 50 %.

The absolute GRFs and joint moments were preferred to accurately measure the physical pressure delivered to the ankle and knee joint. This method offers a better understanding of the pressures the joints face, which is essential, taking into account an association between physical pressure and the occurrence of OA. By illustrating absolute values, the research aims to emphasize bodily mechanisms that lead to the likelihood of degeneration of joints.

The BMI changes impacted muscle electromyographic activities (Fig. 5). These alterations were particularly noticeable in the quadriceps and hamstring muscles during the early to midstance phase, while the gastrocnemius muscles showed the opposite pattern (Fig. 5). Specifically, the vastus medialis activation demonstrated a gradual increase in activity, mainly between 15 % and 50 % of the stance phase. For the rest of the quadriceps muscles, the obese group displayed a significant and more pronounced activation augmentation than the other participants. Regarding the hamstrings, higher muscle activation was observed in the lateral hamstring for the obese and overweight groups. In contrast, only the obese group exhibited greater activation in the medial hamstring. In comparison to the hamstring component, the lateral gastrocnemius exhibited a distinctive augmentation in activation during late stance when compared to the other participants (Fig. 5) ($P<0.001$).

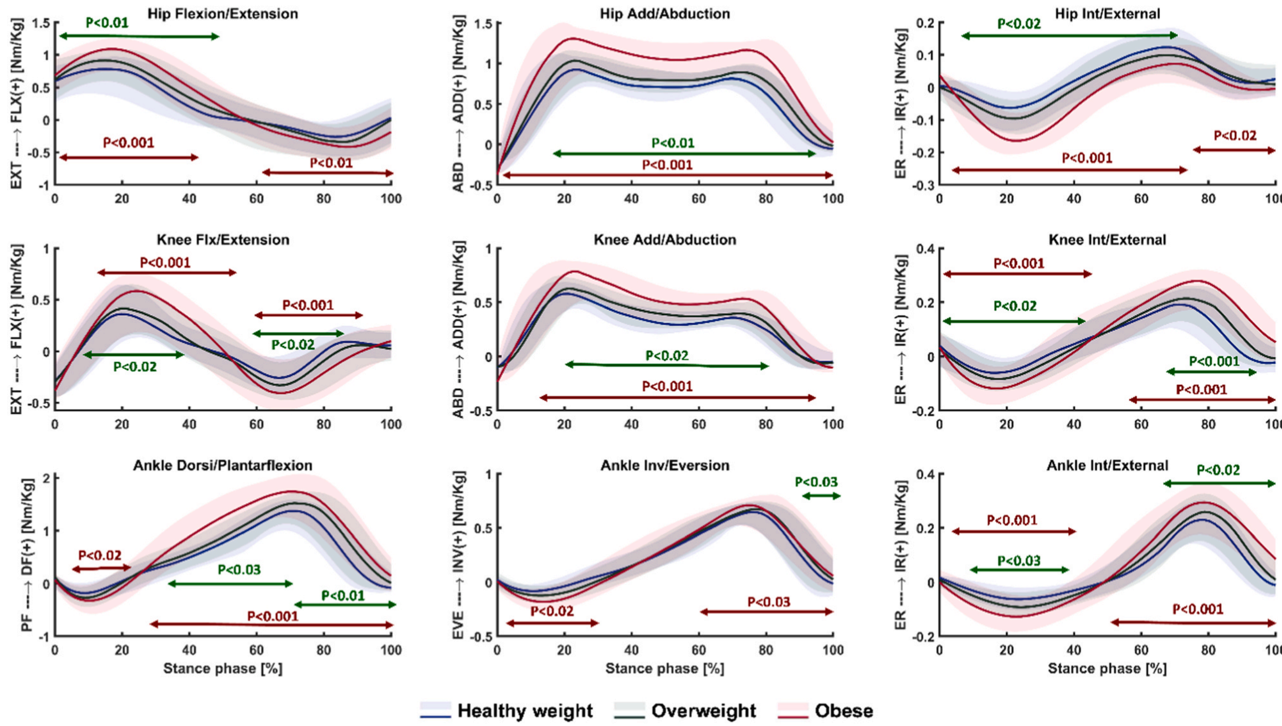

Fig. 3. Lower extremity joints moment for the Healthy weight, Overweight, and Obese participants, with region statistical significance, indicated for Obese Vs Healthy weight (◀——▶) and Overweight Vs. Healthy weight (◀——▶).

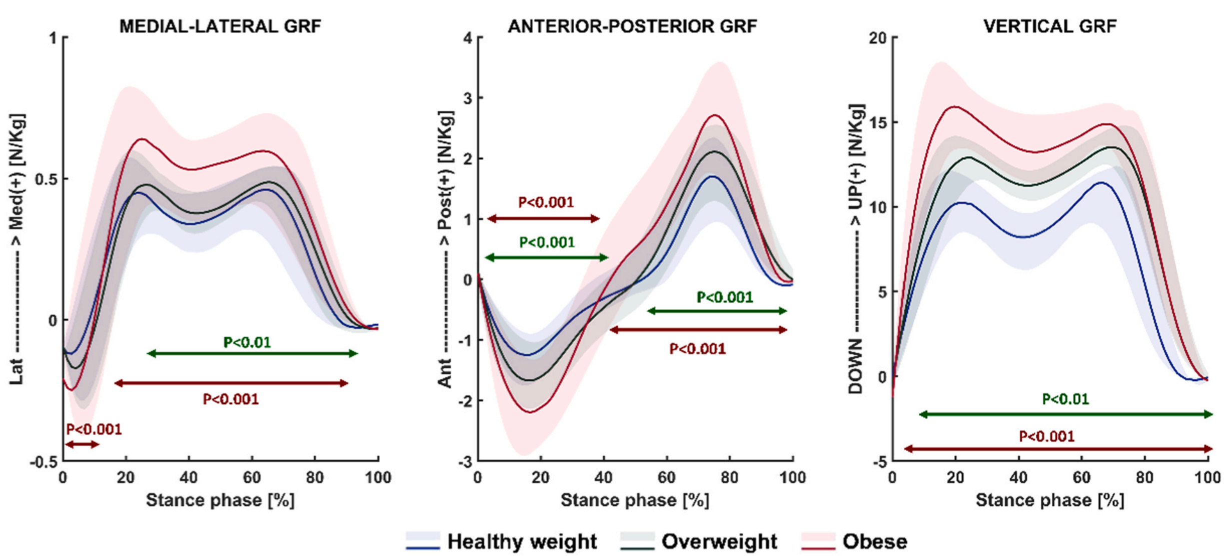

Fig. 4. Ground reaction force components for the Healthy weight, Overweight, and Obese participants, with region statistical significance, indicated for Obese Vs Healthy weight (◀——▶) and Overweight Vs. Healthy weight (◀——▶).

4. Discussion

This study aimed to investigate the impact of BMI changes on gait by examining the comprehensive 3D joint angular motions, moments, ground reaction forces, and muscle activations. Three cohorts were included: healthy controls, overweight, and obese individuals. The findings of this study offer novel insights into the relationships between BMI and the lower limb's joint kinematics and kinetics, as well as the surrounding muscle activities. Furthermore, the findings demonstrate that increases in body mass are associated with higher joint biomechanical burden during walking.

Our data exhibited that a higher BMI was associated with an increased hip flexion angle during the early stance phase (Fig. 2). However, this increase did not show a consistent progression among the three cohorts, as a noticeable leap was observed specifically among the obese participants. As the stance phase progressed, these differences became less prominent in the mid-region. They reversed in direction by the end of the stance phase, transitioning to an extension similar to the initial flexion trends. These alterations in the sagittal angular motion of the hip align with previously reported findings in the literature [21,24,26,43–45]. For instance, McMillan et al. [46] found a significantly greater hip extension during the latter half of the stance phase. Shultz et al. [22] reported a non-significant increase in hip flexion within the same time frame. Discrepancies between these studies could be

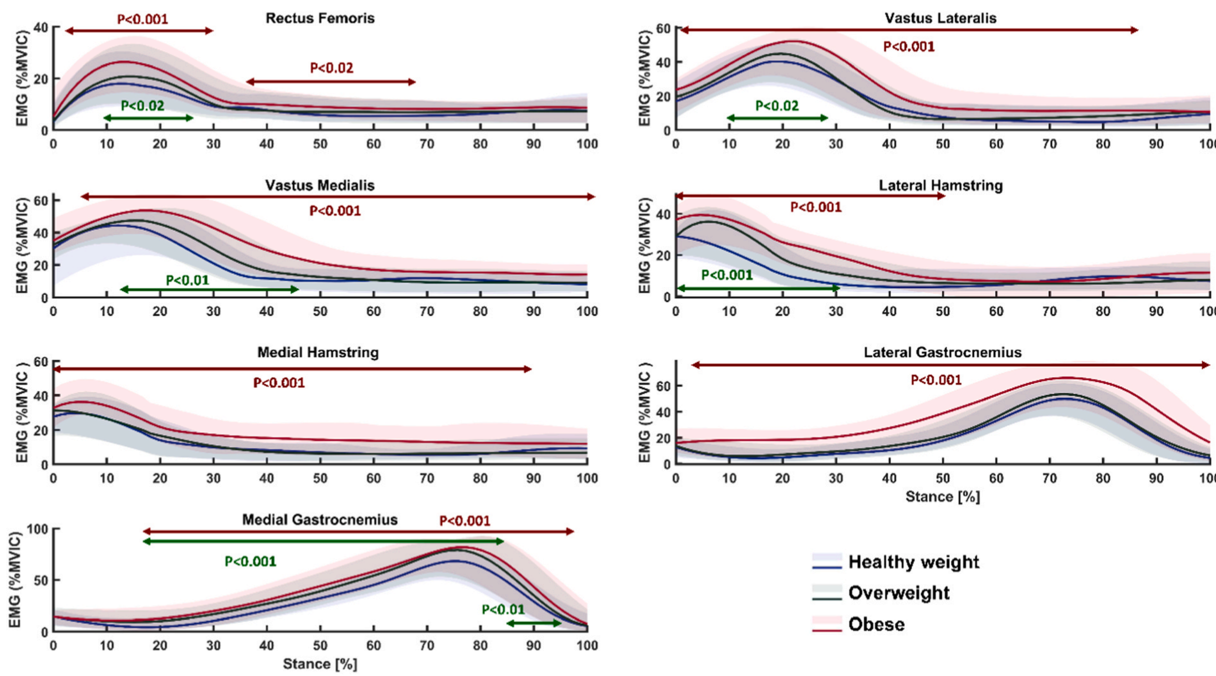

Fig. 5. EMG signals of the rectus femoris, vastus lateralis and medialis, lateral and medial hamstrings, and lateral and medial gastrocnemius, for the Healthy weight, Overweight, and Obese participants, with region statistical significance, indicated for Obese Vs Healthy weight (◀—▶) and Overweight Vs. Healthy weight (◀—▶).

attributed to variations in experimental protocols, participant selection, and, notably, the considerably higher BMI values observed among certain obese participants in the survey by Shultz. The hip flexion moment exhibited a similar trend to the angular patterns, with a more gradual increase observed between the cohorts during the early stance phase. However, this progressive increase diminished by the second half of the stance phase, resulting in minimal differences between all participants. The higher flexion moment during the early stance phase has been well-documented in the literature and used to explain the increased flexion angle observed in obese individuals [20].

Obese subjects showed noticeably larger hip adduction angles and moments in the frontal and transverse planes linked to prolonged external rotations and moments. These results are consistent with most research examining how BMI changes affect hip biomechanics. [19,21,23,47–49]. One explanation for this observation is the weakening of hip abductor muscles, such as the gluteus medius, which stabilize the hip joint and prevent excessive adduction and external rotation [50]. In obese individuals, these muscles may weaken due to the increased load they have to bear [51]. Higher adduction-external moments may arise from a reduced capacity to control hip adduction and external rotation due to the weakening of the hip abductors.

Regarding the knee, the results of our study show that obese participants had a significantly higher knee flexion moment during the first half of the stance phase ($P<0.0001$). In contrast, the overweight group showed no differences from the healthy control group (Fig. 3**)**. Nonetheless, this parameter was gradually modified during the latter part of the stance phase. Noticeably lower flexion angles offset this increase in the sagittal moment throughout the stance phase. **(**Fig. 2). The combination of reduced flexion angles and higher flexion moments likely contributes to minimizing fatigue within the extensor mechanism [52]. This is due to the enhanced effectiveness of the quadriceps muscles in offsetting sagittal knee moments at lower flexion angles [53–55]. Increased angles and moments in other lower limb joints, such as the hip and ankle, accompanied the sagittal plane adaptation seen during gait. This demonstrates how obese people can reorganize their neuromuscular function, which may improve damping factors and allow for a better distribution of the significant increase in ground reaction forces among these three joints[1,56]. It is crucial to remember that, despite these adjustments, there is still a discernible rise in knee loading because of the general increase in moments at all three joints. Moreover, the observed variability highlights how difficult it is to determine joint loads during gait precisely based only on body mass and ground reaction forces—especially when assuming that predicted joint kinematics and kinetics will be used.

During this investigation, the kinematics and kinetics observed in obese participants were comparable to those reported in women during the later stages of pregnancy. After delivery [57,58] and in-service members walking with and without carrying loads [59,60]. Pregnancy led to a significant increase in body mass and hip/ankle moment, while it did not impact the knee moment. On the other hand, the study involving service members found that walking with an additional load of 15 % and 30 % of body weight resulted in increased sagittal moments at the hip, knee, and ankle compared to normal walking. These studies, along with others that align with our current investigation, confirm that BMI alterations place an additional burden on the ankle joint, particularly during the latter half of the stance cycle, where obese individuals experienced a 23 % increase in total angular impulse. Once again, these findings highlight how individuals adapt their neuromuscular function in response to BMI changes, aiming to optimize the kinematics and kinetics of the lower extremities for improved distribution of joint loads. Further investigations are warranted to gain a deeper understanding of the alterations in internal load on soft tissues due to BMI changes, representing an important advancement in our knowledge of this aspect [61,62].

Obese participants were found to have significantly higher adduction moments during the stance phase. This observation aligns with several studies that have found a correlation between obese individuals' higher fatty tissue levels between their thighs and greater external knee adduction moments[19,63]. These elevated knee adduction moments may indicate the presence of greater compressive forces concentrated in the medial compartment of the tibiofemoral joint [5,13]. This mechanical factor has been positively associated with the severity and progression of osteoarthritis, confirming previous findings that obesity is a significant biomechanical risk factor for knee osteoarthritis due to abnormal frontal knee joint loading [25]. Regarding the ankle joint, obese participants exhibited more internal transversal rotations and demonstrated higher external moments at the onset of the stance phase. These results agree with the well-documented phenomenon of an "out-toe" gait observed in obese individuals. The reduced external ankle moments at the beginning of the stance may contribute to a decrease in lateral body motion, thereby enhancing gait stability [50].

As per one study, the movement of ankle and knee joints during walking of young adults depends on the combined effects of BMI and arch height. The greater force required for plantar-flexion movement was associated with increased BMI. On the contrary, side-to-side ankle motion and abduction movement of the knee were associated with lower arch height [64]

Our findings regarding the stride characteristics of obese participants align with the studies conducted by Spyropoulos et al. [65] and Li et al. [66]. Spyropoulos et al. [65] reported that obese individuals tend to have longer periods of grounding and walk at a slower pace, using shorter steps and a lower frequency of strides than those with a healthy weight. Similarly, in our study, obese participants displayed similar patterns. Li et al. [66] also reported nearly identical results when studying obese children. The angular kinematic results we obtained were in line with the findings of Spyropoulos et al. [65]. Specifically, our obese participants exhibited less knee flexion and increased ankle dorsiflexion, corresponding to a more upright walking pattern. During the stance phase, knee flexion decreases due to simultaneous and opposing rotations of the thigh and leg. This leg rotation typically reduces ankle plantar flexion since the foot remains horizontally stationary on the ground. Consequently, we can conclude that obese individuals tend to adopt a more vertical walking pattern than individuals without obesity, which could explain the observed longer duration of strides and shorter stride length within this particular group.

In contrast to previous studies that found no significant impact of obesity on electromyography (EMG) measures of lower limb muscle activity in children and adolescents [67–70], our research uncovered distinct changes in the activation patterns of the quadriceps, hamstring, and gastrocnemius muscles during gait in individuals with obesity. The dissimilarities in demographics and experimental protocols among various studies may account for the disparity in our findings compared to previous investigations. Significant EMG results in obese individuals with thick thighs suggest increased muscle activation caused by weight gain and shifted kinematics. Higher rates of obesity and lifestyle choices all contribute to muscular tension and deterioration. Specific interventions are essential in increasing muscular function and movement.

During our study, we observed sustained activation of the gastrocnemius and quadriceps muscles throughout the early and late stages of the stance phase in participants with higher BMI. These prolonged muscle activation patterns were predominantly evident in the obese group, excluding the lateral hamstring and medial gastrocnemius muscles. This finding supports the concept that there might be a threshold BMI value beyond which individuals begin to adapt to altered neuromuscular patterns [71].

Similarly, research involving military personnel has demonstrated that increased load carriage leads to extended durations of lower limb muscle activity during gait in healthy individuals [72]. The prolonged muscle activity observed during the stance phase among individuals with obesity may signify a compensatory strategy, indicating reduced confidence in joint stability and utilization compared to healthy and overweight individuals. Furthermore, the altered muscle activities associated with a higher BMI category may be connected to changes in predicted joint kinetics. The increased flexion moment in the knee joint during early stance typically requires additional quadriceps activation to maintain balance. Simultaneously, hip flexion and knee adduction moments primarily drive the activation of the medial and lateral hamstring muscles in the early stance phase. The gastrocnemius muscle exhibits greater activation during the late stance phase to propel the body forward [73], which is expected to increase with higher dorsiflexion moments. These observations remained consistent across cohorts, with progressive and non-progressive increases in joint moment and muscle activation. The heightened muscle activities identified in our study contribute to fatigue and disrupt the active mechanism for shock absorption in the knee joint [74]. Consequently, this may create an unfavorable mechanical environment that accelerates the risk of osteoarthritis damage. Notably, these findings provide a more substantial foundation for understanding the altered muscle activities associated with a higher BMI category, particularly in relation to joint kinetics.

This study has several limitations that merit discussion. Firstly, the average BMI of our obese group was 32.87 kg/m^2, which is lower than the BMI range typically examined in previous studies on obesity [21,24,75]. Consequently, our results may only reflect individuals within this specific BMI range, which could explain the discrepancies observed between our findings and those of prior studies. Second, because skin movement artifacts can introduce errors in segment position and orientation determination, it is crucial to consider this when using skin-mounted markers. This restriction applies to all research using this methodology, especially when the subjects are obese [76]. Thirdly, there have been concerns expressed about the use of EMG measurements with obese individuals. These worries include a decrease in the strength of the measured signal and an increase in interference from nearby muscle groups [1,51,75]. Precautionary measures followed established guidelines to address these issues [77].

5. Conclusion

The study comprehensively analyzed biomechanical changes between BMI groups during walking. Significant variations were found in lower limb muscle activity, motion, and forces, indicating gait adaptations vary with body mass.

Author contribution

All authors have read and approved this submission; the Corresponding author (M. A) carried out the definition and design of the work; all participated in the development and analysis of the work; and finally, the manuscript was written by all authors.

CRediT authorship contribution statement

Malek Adouni: Visualization, Validation, Supervision, Resources, Project administration, Formal analysis, Data curation. **Fadi Alkhatib:** Formal analysis, Conceptualization. **Tanvir R. Faisal:** Writing – original draft, Visualization, Validation, Conceptualization. **Raouf Hajji:** Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare no conflicts of interest or financial disclosures related to this research. This study received no external funding, and the authors

Acknowledgment

The work is supported by a grant from the Kuwait Foundation for the Advancement of Sciences (CR20–13MM-01).

References

[1] R. Andersen, Obesity: Etiology, Assessment, Treatment, and Prevention, Human Kinetics, 2003.
[2] L. Sharma, et al., The mechanism of the effect of obesity in knee osteoarthritis: the mediating role of malalignment, Arthritis Rheum. 43 (3) (2000) 568–575.
[3] Diseases, N.i.o.d.a.d.a.k. . 2021[cited 2021 2021]; Available from: Overweight & Obesity Statistics⟨https://wwwniddk.nih.gov/health-information/health-statistics/overweight-obesity⟩.Overweight & Obesity Statistics⟨https://

wwwniddknih.gov/health-information/health-statistics/overweight-obesity⟩.⟨https://www.niddk.nih.gov/health-information/health-statistics/overweight-obesity⟩..

[4] H.J. Samvelyan, et al., Models of Osteoarthritis: Relevance and New Insights, Calcif. Tissue Int. 109 (3) (2021) 243–256.

[5] M. Adouni, A. Shirazi-Adl, Partitioning of knee joint internal forces in gait is dictated by the knee adduction angle and not by the knee adduction moment, J. Biomech. 47 (7) (2014) 1696–1703.

[6] F.C. Anderson, M.G. Pandy, Dynamic optimization of human walking, J. Biomech. Eng. 123 (5) (2001) 381–390.

[7] T.P. Andriacchi, S. Koo, S.F. Scanlan, Gait mechanics influence healthy cartilage morphology and osteoarthritis of the knee, J. Bone Jt. Surg. Am. 91 (2009) 95–101. **Suppl 1**(Suppl 1).

[8] J.L. Astephen, et al., Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity, J. Orthop. Res. 26 (3) (2008) 332–341.

[9] H.A. Gray, et al., Three-dimensional motion of the knee-joint complex during normal walking revealed by mobile biplane x-ray imaging, J. Orthop. Res 37 (3) (2019) 615–630.

[10] G.T. Harding, et al., Body mass index affects knee joint mechanics during gait differently with and without moderate knee osteoarthritis, Osteoarthr. Cartil. 20 (11) (2012) 1234–1242.

[11] J.-S. Li, et al., Six degree-of-freedom knee joint kinematics in obese individuals with knee pain during gait, PloS One 12 (3) (2017) e0174663.

[12] X. Zeng, et al., Relationship between Kellgren-Lawrence score and 3D kinematic gait analysis of patients with medial knee osteoarthritis using a new gait system, Sci. Rep. 7 (2017).

[13] M. Adouni, A. Shirazi-Adl, Evaluation of knee joint muscle forces and tissue stresses-strains during gait in severe OA versus normal subjects, J. Orthop. Res 32 (1) (2014) 69–78.

[14] J.L. Astephen, et al., Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels, J. Biomech. 41 (4) (2008) 868–876.

[15] A.J. Baliunas, et al., Increased knee joint loads during walking are present in subjects with knee osteoarthritis, Osteoarthr. Cartil. 10 (7) (2002) 573–579.

[16] K.R. Kaufman, et al., Gait characteristics of patients with knee osteoarthritis, J. Biomech. 34 (7) (2001) 907–915.

[17] L. Murphy, et al., Lifetime risk of symptomatic knee osteoarthritis, Arthritis Rheum. 59 (9) (2008) 1207–1213.

[18] R. Lee, W.F. Kean, Obesity and knee osteoarthritis, Inflammopharmacology 20 (2) (2012) 53–58.

[19] A.G. McMillan, et al., Frontal and sagittal plane biomechanics during drop jump landing in boys who are obese, Pediatr. Phys. Ther. 22 (1) (2010) 34–41.

[20] J.S. Dufek, et al., Effects of overweight and obesity on walking characteristics in adolescents, Hum. Mov. Sci. 31 (4) (2012) 897–906.

[21] R. Mahaffey, et al., Biomechanical characteristics of lower limb gait waveforms: Associations with body fat in children, Gait Posture 61 (2018) 220–225.

[22] S.P. Shultz, et al., Body size and walking cadence affect lower extremity joint power in children's gait, Gait Posture 32 (2) (2010) 248–252.

[23] F.R. Silva, et al., Biomechanical alterations of gait on overweight subjects, Res. Biomed. Eng. 34 (4) (2018) 291–298.

[24] P. DeVita, T. Hortobagyi, Obesity is not associated with increased knee joint torque and power during level walking, J. Biomech. 36 (9) (2003) 1355–1362.

[25] G.T. Harding, et al., Obesity is associated with higher absolute tibiofemoral contact and muscle forces during gait with and without knee osteoarthritis, Clin. Biomech. 31 (2016) 79–86.

[26] G.T. Harding, et al., Body mass index affects knee joint mechanics during gait differently with and without moderate knee osteoarthritis, Osteoarthr. Cartil. 20 (11) (2012) 1234–1242.

[27] H.E. Badr, N.M. Shah, M.A. Shah, Obesity among Kuwaitis aged 50 years or older: prevalence, correlates, and comorbidities, Gerontologist 53 (4) (2013) 555–566.

[28] I.A. Baert, et al., Gait characteristics and lower limb muscle strength in women with early and established knee osteoarthritis, Clin. Biomech. 28 (1) (2013) 40–47.

[29] S.I. Ahmad, S.K. Imam, Obesity: A Practical Guide, Springer, 2015.

[30] F. Hu, Obesity Epidemiology, Oxford University Press, 2008.

[31] M.W. Whittle, Clinical Gait Analysis: A Review, Hum. Mov. Sci. 15 (3) (1996) 369–387.

[32] J.M. Wilken, et al., Reliability and minimal detectible change values for gait kinematics and kinetics in healthy adults, Gait Posture 35 (2) (2012) 301–307.

[33] C. Kirtley, Clinical Gait Analysis: Theory and Practice, Elsevier Health Sciences, 2006.

[34] S.L. Delp, et al., OpenSim: open-source software to create and analyze dynamic simulations of movement, IEEE Trans. Biomed. Eng. 54 (11) (2007) 1940–1950.

[35] V. Medved, et al., Gait Analysis. Measurement and Analysis of Human Locomotion, Springer, 2022, pp. 219–255.

[36] T.F. Besier, et al., Knee muscle forces during walking and running in patellofemoral pain patients and pain-free controls, J. Biomech. 42 (7) (2009) 898–905.

[37] M. Jacquelin Perry, Gait Analysis: Normal and Pathological Function, SLACK, New Jersey, 2010.

[38] P. de Leva, Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters, J. Biomech. 29 (9) (1996) 1223–1230.

[39] E.S. Grood, W.J. Suntay, A joint coordinate system for the clinical description of three-dimensional motions: application to the knee, J. Biomech. Eng. 105 (2) (1983) 136–144.

[40] J. Perry, Gait analysis: normal and pathological function, J. Pediatr. Orthop. 12 (6) (1992) 815.

[41] Astephen, J.L., Biomechanical Factors in the Progression of Knee Osteoarthritis, in School of Biomedical Engineering. 2007, Dalhousie university: Halifax. p. 216.

[42] T.C. Pataky, One-dimensional statistical parametric mapping in Python, Comput. Methods Biomech. Biomed. Eng. 15 (3) (2012) 295–301.

[43] A.G. Fischer, A. Wolf, The effects of body weight unloading on kinetics and muscle activity of overweight males during Overground walking, Clin. Biomech. 52 (2018) 80–85.

[44] D.J. Haight, et al., A comparison of slow, uphill and fast, level walking on lower extremity biomechanics and tibiofemoral joint loading in obese and nonobese adults, J. Orthop. Res. 32 (2) (2014) 324–330.

[45] K.F.E. MacLean, J.P. Callaghan, M.R. Maly, Effect of obesity on knee joint biomechanics during gait in young adults, Cogent Med. 3 (1) (2016) 1173778.

[46] A. McMillan, et al., Sagittal and frontal plane joint mechanics throughout the stance phase of walking in adolescents who are obese, Gait Posture 32 (2) (2010) 263–268.

[47] E.M. Russell, J. Hamill, Lateral wedges decrease biomechanical risk factors for knee osteoarthritis in obese women, J. Biomech. 44 (12) (2011) 2286–2291.

[48] J. Sun, et al., Finite element analysis of the valgus knee joint of an obese child, Biomed. Eng. Online 15 (Suppl 2) (2016) 158.

[49] D. Yocum, et al., Wide step width reduces knee abduction moment of obese adults during stair negotiation, J. Biomech. 75 (2018) 138–146.

[50] S.C. Wearing, et al., Musculoskeletal disorders associated with obesity: a biomechanical perspective, Obes. Rev. 7 (3) (2006) 239–250.

[51] P. Amiri, et al., Obesity is associated with prolonged activity of the quadriceps and gastrocnemii during gait, J. Electromyogr. Kinesiol. 25 (6) (2015) 951–958.

[52] R.C. Browning, R. Kram, Effects of obesity on the biomechanics of walking at different speeds, Med Sci. Sports Exerc 39 (9) (2007) 1632–1641.

[53] M. Adouni, A. Shirazi-Adl, Consideration of equilibrium equations at the hip joint alongside those at the knee and ankle joints has mixed effects on knee joint response during gait, J. Biomech. 46 (3) (2013) 619–624.

[54] M. Adouni, A. Shirazi-Adl, R. Shirazi, Computational biodynamics of human knee joint in gait: from muscle forces to cartilage stresses, J. Biomech. 45 (12) (2012) 2149–2156.

[55] F. Al Khatib, et al., Biomechanical characteristics of the knee joint during gait in obese versus normal subjects, Int. J. Environ. Res. Public Health 19 (2) (2022) 989.

[56] E. Husni, A N. Look. Obes. Osteoarthr. (2015) cited 2015 Jan. 6].

[57] M. Branco, R. Santos-Rocha, F. Vieira, Biomechanics of gait during pregnancy, Sci. World J. 2014 (2014).

[58] T. Foti, J.R. Davids, A. Bagley, A biomechanical analysis of gait during pregnancy, JBJS 82 (5) (2000) 625.

[59] L. Ren, R.K. Jones, D. Howard, Dynamic analysis of load carriage biomechanics during level walking, J. Biomech. 38 (4) (2005) 853–863.

[60] P.M. Quesada, et al., Biomechanical and metabolic effects of varying backpack loading on simulated marching, Ergonomics 43 (3) (2000) 293–309.

[61] T.R. Faisal, M. Adouni, Y.Y. Dhaher, The effect of fibrillar degradation on the mechanics of articular cartilage: a computational model, Biomech. Model. Mechanobiol. (2019) 1–19.

[62] M. Adouni, et al., A multiscale synthesis: characterizing acute cartilage failure under an aggregate tibiofemoral joint loading, Biomech. Model Mechanobiol. (2019).

[63] L.F.A. Selistre, et al., The relationship between external knee moments and muscle co-activation in subjects with medial knee osteoarthritis, J. Electromyogr. Kinesiol. 33 (2017) 64–72.

[64] D. Kim, C.L. Lewis, S.V. Gill, Effects of obesity and foot arch height on gait mechanics: a cross-sectional study, PLoS One 16 (11) (2021) e0260398.

[65] P. Spyropoulos, et al., Biomechanical gait analysis in obese men, Arch. Phys. Med. Rehabil. 72 (13) (1991) 1065–1070.

[66] J.X. Li, L. Wang, D.Q. Xu, Gait and postural stability in obese and nonobese prepubertal children, J. Biomech. 40 (2)) (2007) S522.

[67] D.L. Menkes, R. Pierce, Needle EMG muscle identification: a systematic approach to needle EMG examination, Clin. Neurophysiol. Pract. 4 (2019) 199–211.

[68] A. Hills, A. Parker, Electromyography of walking in obese children, Electromyogr. Clin. Neurophysiol. 33 (4) (1993) 225–233.

[69] W. Maktouf, et al., Interactions among obesity and age-related effects on the gait pattern and muscle activity across the ankle joint, Exp. Gerontol. 140 (2020) 111054.

[70] F.R.P. de Carvalho, A.Td.C.F. Martins, A.M.M.B. Teixeira, Analyses of gait and jump tasks in female obese adolescents, Pediatr. Exerc. Sci. 24 (1) (2012) 26–33.

[71] J. Runhaar, et al., A systematic review on changed biomechanics of lower extremities in obese individuals: a possible role in development of osteoarthritis, Obes. Rev. 12 (12) (2011) 1071–1082.

[72] S.A. Birrell, R.A. Haslam, The effect of military load carriage on 3-D lower limb kinematics and spatiotemporal parameters, Ergonomics 52 (10) (2009) 1298–1304.

[73] M. Adouni, A. Shirazi-Adl, H. Marouane, Role of gastrocnemius activation in knee joint biomechanics: gastrocnemius acts as an ACL antagonist, Comput. Methods Biomech. Biomed. Eng. 19 (4) (2016) 376–385.

[74] K.L. Bennell, et al., Update on the role of muscle in the genesis and management of knee osteoarthritis, Rheum. Dis. Clin. 39 (1) (2013) 145–176.

[75] G.T. Harding, Obesity, Moderate Knee Osteoarthritis, Knee Jt. Dyn. (2012).

[76] R. Baker, et al., The Conventional Gait Model - Success and Limitations, Springer International Publishing, 2018, pp. 489–508.

[77] G.L. Soderberg, L.M. Knutson, A Guide for Use and Interpretation of Kinesiologic electromyographic data, Phys. Ther. 80 (5) (2000) 485–498.