Comprehensive Biomechanical Analysis of Ankle Joint Kinetics and Plantar Pressure Distribution during Human Gait

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Abstract:- Walking results from a cyclic series of foot movements, with one complete cycle called a gait cycle. Gait analysis is crucial for identifying abnormalities, enhancing athletic performance, improving ergonomics as well as diagnosing and monitoring conditions like Parkinson's disease and cerebral palsy. This study focuses on the Asian population, considering their anthropometric data to develop a foot link model for determining foot forces. We aim to create a low-cost, automated program for foot force analysis to serve as an assistive device for foot pressure pad results. The research analyses ankle joint forces during gait stance in normal volunteers (58 females and 81 males) using ground reaction forces and reverses dynamic equilibrium. Two specific stance phases were examined: mid-stance and push-off. Anthropometric data provided the geometry for equilibrium calculations, and ankle joint forces were determined using a free-body diagram, with gait motion captured via videography. Results indicate the younger males exhibit significantly higher vertical ground reaction forces (VGRF), Achilles tendon forces (T), and ankle joint forces (Jc) compared to females. In contrast, older females show increased foot forces and altered gait mechanics, potentially due to age-related physiological changes. This study offers insights into conditions like flat foot and high arch, providing quick, minimally invasive diagnostic methods for gait-related conditions. Future work will focus on comparing patient kinetics and kinematics before and after physiotherapy, enhancing treatment for altered gaits.

Keywords: Ankle joint, Biomechanics, Dynamic Equilibrium, Foot Pressure Analysis, Gait.

1. Introduction

Walking is the result of a cyclic series of movements of the human lower limb. One complete cycle of the foot is called a gait cycle [1]. Walking offers valuable data for gait analysis, helping identify abnormalities, enhance athletic performance, and improve ergonomics. It is crucial for diagnosing and monitoring conditions such as Parkinson's disease, cerebral palsy, and other neuromuscular disorders [2], [3], [4]. The gait process is primarily separated into the stance phase and the swing phase [5]. As the foot is on the ground, supporting the body's weight, the stance phase begins with heel contact and finishes with toe-off [6]. Plantar pressure measurement and motion analysis are now key methods for studying gait [7], [8], [9].

Numerous studies have analyzed the forces on the foot during different gait phases. Patil's research indicated vertical ground force reactions and ankle joint forces like those found in this study [10], while Gefen et al. observed an increasing trend in ankle joint force from heel strike to push-off phases [11]. Procter et al. noted the activity of the Anterior tibialis tendon during the heel strike phase and the Achilles tendon during the stance phases. Additionally, various studies highlighted the impact of gait velocity on spatial-temporal characteristics and joint dynamics [12].

A lot of research has been conducted on foot force development during gait phases, primarily using European population data as a benchmark [13], [14], [15], [16]. In the present study, we focus on the Asian population due

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to significant differences in anthropometric data [17], [18]. Our goal is to develop a foot link model to determine foot forces and create a low-cost, instantaneous automation program for foot force analysis, serving as an assistive device for foot pressure pad results. Excel is used for automation programs.

2. Method

A. Instrumentation and experimental setup

A gait analysis was carried out on the participant's foot sample. Out of that, 58 were female and 81 were normal foot arch participants. The sample was further classified based on age., as shown in Table No.1. The inclusion criteria were as follows: (1) Individuals aged 18 years and above (2) male, and female (3) Participants having the ability to walk independently. (4) Who exhibit normal foot arch. The exclusion criteria were: (1) Who exhibit flat or high foot arch. (2) foot wound, foot injury. The hospital review board approved this study. The research was carried out following the principles outlined in the 'Declaration of Helsinki'. A written informed consent form was obtained from each participant before their involvement in the study.

B. Instrumentation and experimental setup

A pedobarographic assessment was conducted using the Footwork Pro device, which analyses foot pressure data in conjunction with the Footwork Pro IST software. Concurrently, side-view video footage was recorded to capture the stance phase of gait, with neon markers strategically placed on key lower limb landmarks to facilitate the tracking of the pressure distribution across the foot surface during movement. Throughout the gait cycle, as the foot transitioned from heel strike to toe-off on the pressure pad, the shift in body weight from the heel to the toe was precisely captured by the Footwork system and documented in the corresponding video footage. The software subsequently calculated critical parameters, including maximum and mean foot force, pressure force curves, foot pressure distribution, and the center of gravity trajectory during the stance phase. In preparation for simulating forces within the foot model, comprehensive anthropometric data were meticulously recorded. Partial link model of foot developed for mid stance and Pushoff position as shown in Figure no 1. The gait stance phase analysis specifically focused on the ankle joint and Achilles tendon, which were integral to the conceptualization and development of the foot mechanism model. The magnitudes of forces on the Ankle joint (Jc), Achilles tendon (T), and Tibialis anterior tendon (A) were obtained using the following equilibrium equations. Manual calculation of above method is too length and time taken VBA code is used in Excel programming to automate the equilibrium equation solver.

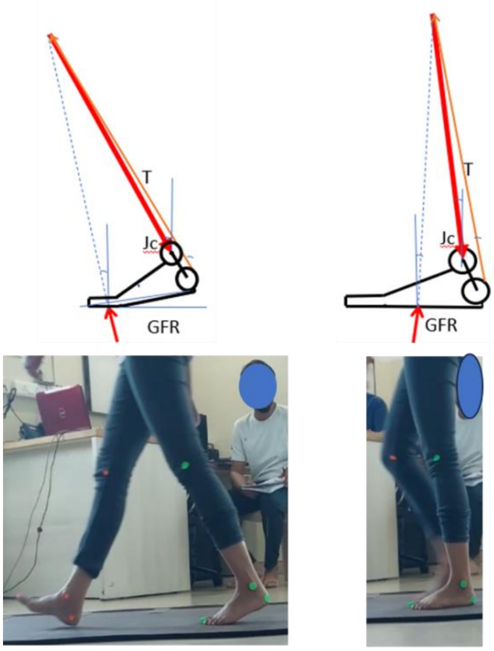

Fig. 1 Partial link model of the foot and Position of foot in stance phases i.e. Mid-stance and Push-off.

C. Statistical Analysis:

Statistical Shapiro-Wilk test was conducted to check the normality of the distribution of the sample. For those not satisfying normality, Mann Whitney U test was used. Statistical significance was set as $\alpha = 0.05$ SPSS (SPSS, IBM, India) was used for statistical analysis. Differences between foot forces Males and Females for Normal foot (based on age) in the mid-stance and push-off phase were found by analysis of variables.

3. Result

Table 1 presents the characteristics data of the male and female participants in Groups A and B. A comparative analysis reveals significant differences between the genders in terms of BMI, weight and height. On average, the male participants are taller than the female participants, which correlates with an increased foot length and weight among the males

Table 1 : Characteristics of the participating subject, Presented as mean value ± Standard deviation.

Gender	Female	Male	P- Value
Group A: Age 18-35	n=33	n=50	
BMI	22.567 ± 4.795	26.54 ± 6.318	0.005
Height (cm)	160.345 ± 6.14	171.744 ± 5.868	< 0.001
Foot length (cm)	23.455 ± 1.24	25.034 ± 1.162	< 0.001
Weight (kg)	58.376 ± 14.698	78.758 ± 21.07	< 0.001
Group B: Age 36-60	n=19	n=17	
BMI	27.362 ± 6.425	26.867 ± 4.069	0.739
Height (cm)	153.948 ± 6.387	167.07 ± 6.035	< 0.001
Foot length (cm)	23.171 ± 0.73	25.056 ± 1.403	< 0.001
Weight (kg)	64.871 ± 16.301	75.078 ± 12.27	0.01
Group C: Age above 60	n=6	n=14	
BMI	30.4 ± 5.304	22.72 ± 1.904	0.061
Height (cm)	152.667 ± 7.567	167.06 ± 8.497	0.05
Foot length (cm)	23.667 ± 0.683	25.8 ± 0.856	< 0.001
Weight (kg)	70 ± 6.261	63.68 ± 9.413	0.904

* Indicate significant difference between the NBMI and HBMI ($p < 0.05$).

Figure 2 illustrates the comparative data between normal foot and flatfoot conditions during the mid-stance phase, focusing on parameters such as the ankle joint angle relative to the vertical axis (Jc°), ground reaction force angle relative to the vertical axis (GRF°), vertical ground reaction force as a percentage of body weight (VGRF), Achilles tendon force as a percentage of body weight (T), and ankle joint force as a percentage of body weight (Jc). Figure 3 provides the comparative analysis during the push-off phase, showing differences in Jc°, VGRF, T, Jc, and foot inclination angle relative to the ground (F°).

During the mid-stance phase, the younger male age group exhibits significantly higher forces in VGRF ($p = 0.043$), T ($p = 0.030$), and Jc ($p = 0.004$), as detailed in Table 2. In the middle age group, males demonstrate an increase in foot forces compared to females, while in the older age group, females exhibit higher forces than males. The ankle joint angle is greater in males than in females in both the younger and middle age groups, but in the older age group, it is higher in females, as illustrated in Figure 2. The ground reaction force angle shows a nearly identical range between genders in the younger and middle age groups, but in the older age group, males (3.207 ± 3.334) demonstrate a higher range compared to females (1.65 ± 2.994). Table no. 2 shows the mean and standard deviation of foot forces and foot angle i.e ground frorce reaction angle and ankle joint angle in male and female among three age group i.e. younger, middle, and older. And significance between male and female at midstance phase.

Table 2 : Foot forces and angle at Mid-stance Position during gait stance phase. Presented as mean value ± Standard deviation.

Variables	Female	Male	P-value
Group A: Age 18-35			
GFR ◦	4.891 ± 2.82	4.942 ± 2.655	0.856
Jc◦	5.303 ± 1.667	5.94 ± 1.994	0.328
VGFR	0.891 ± 0.104	0.954 ± 0.139	0.043*
T	1.548 ± 0.494	1.892 ± 0.588	0.030*
Jc	2.421 ± 0.541	2.808 ± 0.668	0.004*
Group B: Age 36-60			
GFR ◦	4.225 ± 2.923	4.294 ± 2.988	0.568
Jc◦	6.5 ± 2.115	7.059 ± 1.983	0.403
VGFR	0.965 ± 0.093	0.912 ± 0.086	0.07
T	1.6 ± 0.407	1.824 ± 0.498	0.131
Jc	2.545 ± 0.445	2.712 ± 0.516	0.265
Group C: Age above 60			
GFR ◦	1.65 ± 2.994	3.207 ± 3.334	0.386
Jc◦	6.167 ± 2.137	4.5 ± 1.99	0.106
VGFR	0.883 ± 0.117	0.95 ± 0.094	0.308
T	1.017 ± 0.531	1.214 ± 0.568	0.562
Jc	1.867 ± 0.497	2.164 ± 0.573	0.282

* Indicate significant difference between the Male and Female ($p < 0.05$)

Table 2 presents the mean and standard deviation of foot forces, including foot inclination angle relative to the vertical axis and ankle joint angle, for both males and females across three age groups: younger, middle-aged, and older. The table also highlights the statistical significance of differences between males and females during the push-off phase.

In the push-off phase, both younger and middle-aged males and females exhibit similar vertical ground reaction forces (VGRF) of approximately 1.12 times body weight (BW). However, in the older age group, females demonstrate a significantly lower VGRF (0.983 ± 0.098 BW) compared to males (1.14 ± 0.084 BW). Achilles tendon force shows a significantly smaller range in younger (p = 0.004) and older (p = 0.043) males, while in the middle age group, males exhibit a higher Achilles tendon force compared to females. Across all age groups, ankle joint force is consistently higher in males than in females.

Regarding the foot inclination angle with the ground, the younger age group shows nearly identical values between females (11.921 ± 4.775) and males (11.84 ± 4.631). However, in the middle and older age groups, females demonstrate a significantly higher foot inclination angle compared to males, as illustrated in Figure 4. Similarly, the ankle joint angle in the younger age group shows comparable values between females (21.455 ± 3.649) and males (21.4 ± 3.104). In contrast, in the middle and older age groups, females exhibit higher ankle joint angles than males, with the older age group showing a particularly significant difference (p = 0.038), as detailed in Table 3.

Table 3 : Foot forces and angle at Push-Off Position during gait stance phase. Presented as mean value ± Standard deviation.

Variables	Female	Male	P-value
Group A: Age 18-35			
F◦	11.921 ± 4.775	11.84 ± 4.631	0.826
Jc◦	21.455 ± 3.649	21.4 ± 3.104	0.996
VGFR	1.185 ± 0.12	1.188 ± 0.121	0.973
T	3.276 ± 0.646	3.738 ± 0.726	0.004*
Jc	4.397 ± 0.715	4.876 ± 0.776	0.006*
Group B: Age 36-60			
F◦	10.333 ± 3.679	7.722 ± 5.323	0.017*
Jc◦	19.429 ± 3.14	21.222 ± 3.59	0.337
VGFR	1.171 ± 0.11	1.122 ± 0.081	0.115
T	2.933 ± 0.892	3.628 ± 1.098	0.059
Jc	3.35 ± 0.373	4.84 ± 1.158	0.059
Group C: Age above 60			
F◦	10 ± 4.561	6.4 ± 3.169	0.012*
Jc◦	18.167 ± 2.317	21.4 ± 4.477	0.038*
VGFR	0.983 ± 0.098	1.14 ± 0.084	0.005
T	2.4 ± 0.39	3.73 ± 1.147	0.043*
Jc	3.35 ± 0.373	4.84 ± 1.158	0.032*

* Indicates a significant difference between the Males and Female (p < 0.05)

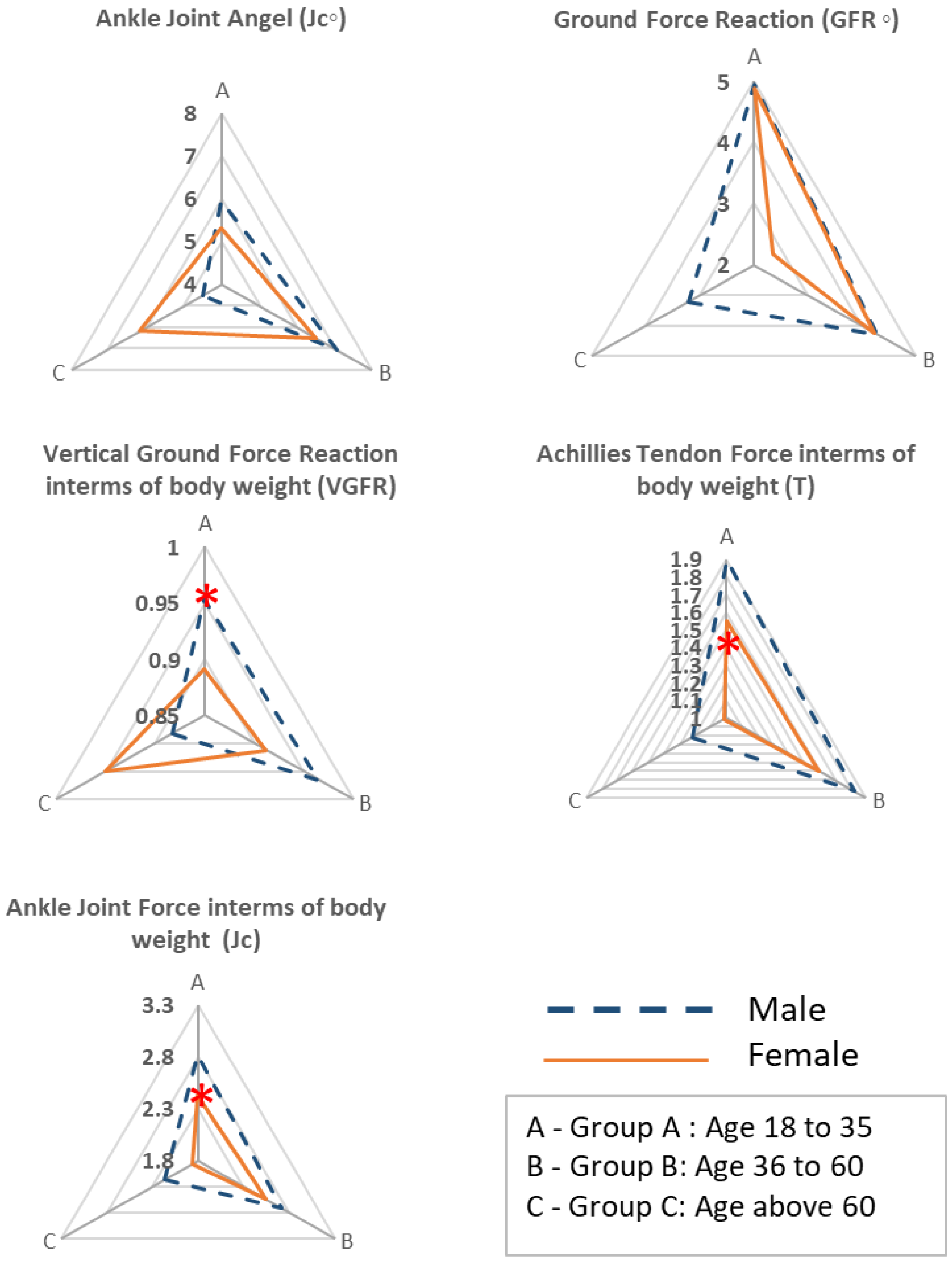

Fig. 2 Ankle joint angle with the vertical axis (Jc°), Ground reaction force angle with the vertical axis (GFR°) Vertical ground reaction force in terms of body weight (VGRF), Achilles tendon force in terms of body weight (T) and Ankle joint force in terms of body weight (Jc) during mid-stance phase of gait stance, * indicates a significant difference between the male and Female ($p < 0.05$)

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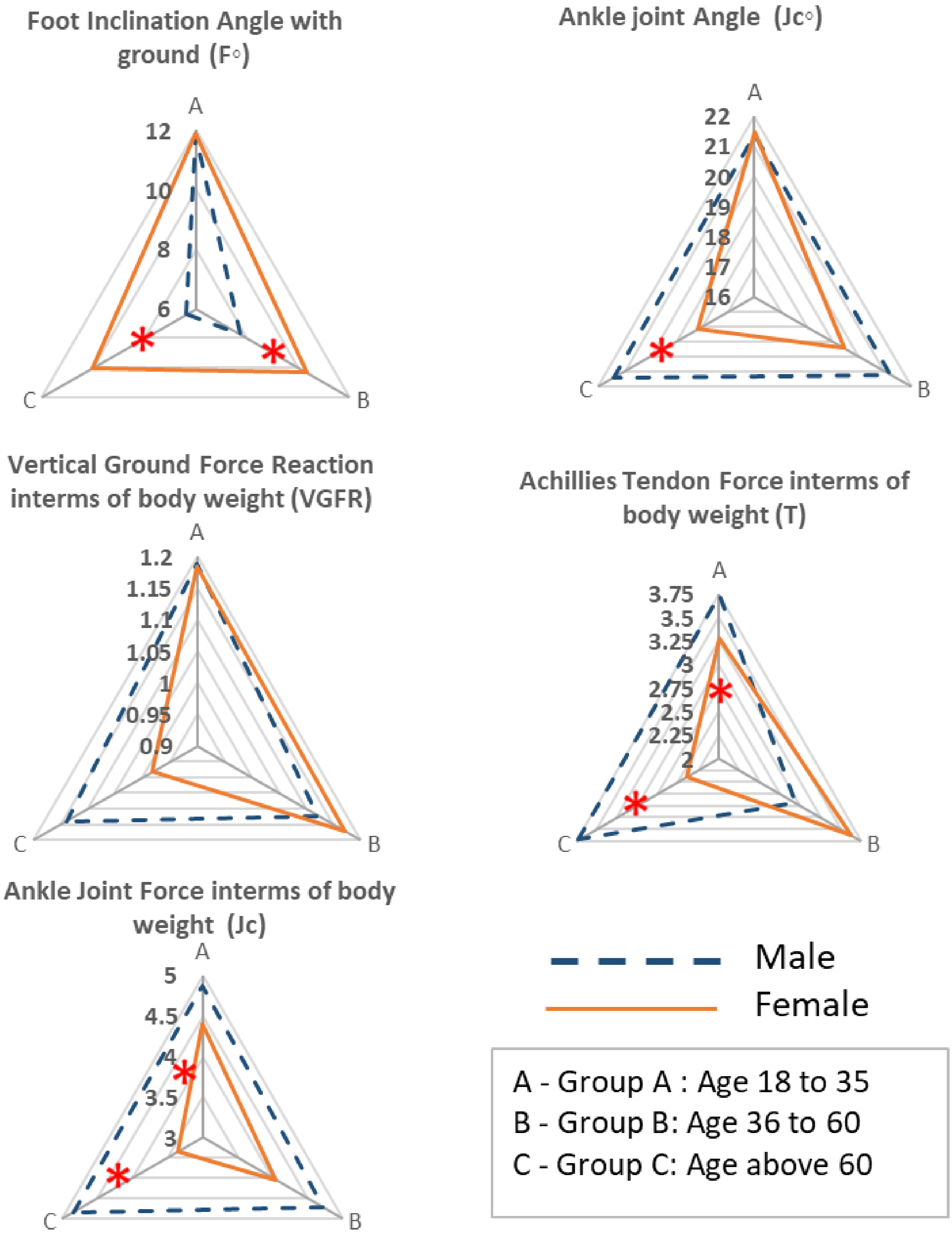

Fig. 2 Vertical ground reaction force in terms of body weight (VGRF), Achilles tendon force in terms of body weight (T), Ankle joint force in terms of body weight (Jc), Ankle joint angle with the vertical axis (Jc°), Foot inclination angle with the horizontal axis (F°) during Push-off phase of gait stance, *indicates a significant difference between the Male and Female ($p < 0.05$)

4. Discussion

The results of this study provide a comprehensive analysis of the biomechanical differences in foot forces and joint angles across different age groups and genders during the mid-stance and push-off phases of gait.

The manual calculation of force measurements is a time-intensive process. To streamline this process, an Excel-based, user-friendly dashboard has been developed. By entering key variables such as age, gender, height, foot length, position of the ground reaction force relative to the heel, and their magnitudes, the dashboard efficiently calculates and outputs foot forces and their directional vectors. Findings of our study suggest that

During the mid-stance phase, younger males exhibit significantly higher vertical ground reaction forces (VGRF), Achilles tendon forces (T), and ankle joint forces (Jc) compared to females, indicating greater biomechanical loading in this group. These findings may be attributed to the higher muscle mass and body weight typically seen in younger males, leading to increased stress on the lower extremities. In the middle age group, males continue to demonstrate higher foot forces than females, suggesting that males maintain a biomechanical advantage during this phase of life. However, in the older age group, this trend reverses, with females showing an increase in foot forces compared to males. This shift could be due to age-related physiological changes, such as decreased muscle mass and bone density in females, leading to altered gait mechanics and compensatory strategies to maintain stability.

The ankle joint angle is consistently higher in males than in females in both the younger and middle age groups, which could reflect the greater joint mobility and dynamic movement patterns in males. In contrast, in the older age group, females exhibit higher ankle joint angles, possibly as a compensatory mechanism to enhance stability as their musculoskeletal system undergoes age-related changes.

The ground reaction force angle shows minimal differences between genders in the younger and middle age groups, suggesting that both males and females employ similar strategies to manage ground forces during mid-stance. However, in the older age group, males display a higher ground reaction force angle than females, which may indicate a continued use of more dynamic movement patterns in older males compared to the more conservative gait strategies seen in older females.

During the push-off phase, both younger and middle-aged males and females exhibit similar VGRF, suggesting that the loading patterns during this phase are relatively consistent across these age groups. However, in the older age group, females demonstrate a significantly lower VGRF compared to males, possibly indicating a reduced ability to generate propulsive forces. This finding could be related to decreased muscle strength and joint mobility in older females, which may lead to a more cautious gait to prevent falls.

In various populations, the magnitude of spatiotemporal parameters, joint dynamics, joint biomechanics and ground reaction forces are affected by gait pattern changes due to different walking speeds. This phenomenon can consequently alter the range of ankle joint forces [12]. In our study maximum Ankle joint force reached at the end of the stance i.e., at Push off is 3.5 to 6.45BW. This agrees with the reported range of peak ankle joint force from 4 to 9 BW for normal walking. [12], [13], [19], [20], [21].

It is noted that the ankle joint force rises as the gait cycle progresses from the heel strike to the push-off phases. This behaviour aligns with the results of Gefen et al. [9], who reported a similar trend with slightly different values. In our study the ankle joint force values are 1.48 times body weight mid-stance, and 6.4 times body weight (6.4 BW) at push-off. In comparison, Gefen et al. reported values of 2.25 times body weight (2.25 BW) at heel strike, 3.58 times body weight (3.58 BW) at mid-stance, and 5 times body weight (5 BW) at push-off [11]. This consistency highlights the reliability of our findings.

The study also shows that the Anterior Tibialis tendon is active in the heel strike phase, up to 12% of the gait cycle while the Achilles tendon is active in the flat foot, mid stance, and push-off phases. These results align with those reported by P. Procter et.al.[12], who observed that the Anterior Tibial group tendon is active up to 15% of the gait cycle, while the Achilles tendon is active from 15% to 55% of the gait cycle.

The Achilles tendon force varies across age groups, with males showing significantly lower forces in both the younger and older age groups, while in the middle age group, males exhibit higher forces compared to females. This variation may reflect differences in tendon elasticity, muscle strength, and the overall biomechanical demands placed on the lower limbs across different stages of life.

The foot inclination angle with the ground shows similar values between genders in the younger age group, indicating comparable foot positioning during the push-off phase. However, in the middle and older age groups, females exhibit significantly higher foot inclination angles, which could be a compensatory response to maintain balance and stability as they age.

Similarly, the ankle joint angle shows little difference between genders in the younger age group, but in the middle and older age groups, females demonstrate higher ankle joint angles, particularly in the older age group where the difference is statistically significant. This finding suggests that females may adopt a different biomechanical strategy to maintain effective propulsion and stability as they age, potentially due to the decline in muscle and joint function.

Future research should concentrate on evaluating the dynamics and motion patterns of individuals before and after the implementation of physiotherapy and exercise interventions for those with mechanically altered gaits. Follow-up assessments should be performed at intervals of one month, three months, six months, and one year to monitor gait improvements, particularly in terms of foot force development. To ensure more robust and generalizable findings, studies should include a larger sample size. Additionally, the results should be validated through in-person interviews to collect qualitative testimonials.

This study, being the first of its kind, explores the kinematics and kinetics of the gait stance phase using an assistive device equipped with a pressure pad. This device enables direct measurement of foot force development, providing a cost-effective and time-efficient approach by leveraging principles of body equilibrium mechanics.

5. Conclusion

This study reveals significant gender and age-related differences in foot forces and gait mechanics during the mid-stance and push-off phases. Younger males exhibit higher biomechanical forces, while older females show altered force patterns and joint angles, potentially due to age-related changes. The development of an Excel-based dashboard facilitates efficient and accurate calculation of foot forces, supporting future research and clinical assessments.

The study provides valuable information for creating personalized rehabilitation programs aimed at strengthening the Achilles tendon during mid-stance and push-off phases. The automated assistive device helps reduce cost and time for foot force analysis. Simulation of the direction and magnitude of Ground ground reaction force is helpful in the prediction of the risk of fall. Additionally, developing a comprehensive model of the human ankle joint serves multiple purposes, including the design of prosthetic devices and rehabilitation protocols, enabling the replication of natural ankle joint forces to improve walking abilities for amputees and enhancing ergonomics in occupational settings. This research lays a crucial foundation for various applications, including sports performance, clinical interventions, and assistive technologies.

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Conflicts of Interest

Deceleration of Interest – None.

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Ethical Approval

Experimental trials were carried out following approval from Deenanath Mangeshkar Hospital and Research Centre, Pune (IHR_2023_Feb_AS_490). The Study was conducted in accordance with the ethical principles mentioned in the Declaration of Helsinki (2013). All participants gave written informed consent.

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