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Analysis of static pelvic tilt variations in transfemoral prosthesis users: comparison of different socket designs with healthy controls

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ABSTRACT

Aims: The aim of this study was to investigate pelvic tilt angles in patients with transfemoral prosthesis, considering different socket designs, and to compare them with healthy controls.

Methods: In this cross-sectional study, 28 male participants were enrolled, including 14 unilateral transfemoral prosthesis users (prosthesis group) and 14 demographically similar healthy subjects (control group). Pelvic tilt angles in both sagittal and frontal planes were measured using a digital inclinometer mounted on a two-arm caliper.

Results: All participants had anterior pelvic tilt. Within the prosthesis group, there was no significant difference in anterior pelvic tilt and lateral pelvic tilt angles between the prosthetic side and the contralateral side (p=0.106, effect size (ES)=0.464; p=0.055, ES=-0.564, respectively). There was no significant difference in anterior pelvic tilt and lateral pelvic tilt angles between the prosthetic side and the contralateral side of the participants using both quadrilateral socket design and ischial containment socket designs (p=0.499, ES=-0.256; p=0.128, ES=-0.575; p=0.063, ES=-0.703; p=0.612, ES=-0.192, respectively). However, a significant difference was found in both the right and left anterior pelvic tilt angles and the lateral pelvic tilt angles between the prosthesis group and the control group (p=0.001, ES=-0.582; p<0.001, ES=-0.635; p<0.001, ES=-0.797, respectively).

Conclusion: The findings reveal that while anterior pelvic tilt is present in all participants, significant differences exist between prosthesis users and healthy individuals in both anterior and lateral pelvic tilt angles. These results underscore the importance of considering pelvic alignment in the design and fitting of prostheses, potentially in forming clinical practices to enhance the comfort and functionality for transfemoral prosthesis users.

Keywords: Transfemoral prostheses, pelvic tilt angle, anterior pelvic tilt, lateral pelvic tilt

INTRODUCTION

Pelvic tilt (PT) is defined as the position of the pelvis in the sagittal plane in a static posture. PT typically refers to the angle in the sagittal plane where the line joining the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) intersects a horizontal line.[1] Anterior pelvic tilt (APT) is characterized by the ASIS positioning lower than the PSIS in the sagittal plane or undergoing a downward rotation relative to the PSIS. Posterior pelvic tilt (PPT) is defined by the elevation of the ASIS above the PSIS in the sagittal plane or its rotational movement exhibiting an upward inclination relative to the PSIS.[2] APT angles in asymptomatic individuals have been reported to be in the average range of 6-7° for both sexes.[3] Changes in PT have been associated with many musculoskeletal conditions, including knee osteoarthritis,[4] low back pain[5] and lumbar spinal stenosis.[6] In addition, these changes are likely to affect lower limb alignment, balance and posture.

Unilateral lower limb amputation can lead to significant changes, including altered gait, imbalance, and compensatory movements. It often causes increased strain on the remaining limb, potential joint pain, and muscle imbalances. There may also be changes in posture, pelvic tilt, and mobility, as well as a need for prosthetics and rehabilitation to restore function and stability.[7] In addition, quality of life and body image perception of patients with amputation may be impaired.[8]

The prosthetic socket component assumes a pivotal role in exerting influence over the strength of the residual limb.[9] The shape of the socket interacting with the stump has undergone various changes over time. The development of ischial containment socket (ICS) designs in the early 1980s,[10] in contrast to the previously prevalent quadrilateral sockets, aimed to place the femur in an adducted position. This positioning enhances gait efficiency through gluteus medius

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muscle movement.[11] Studies have demonstrated that ICS designs that are found to position the femur more medially[12] reduce energy consumption while walking compared to a quadrilateral socket[13] and improve the metabolic cost of walking, along with a reduction in lateral compensatory movements of the trunk.[14] Contemporary socket designs surrounding the ischio pubic ramus have emerged as alternatives to ICS designs.[15]

Several investigations have explored pelvic kinematics in both the sagittal and frontal planes during walking among individuals with TFA. In the sagittal plane, it was noted that TFA individuals exhibited increased APT angles in comparison to healthy controls.[16,17] Regarding the frontal plane, it was determined that pelvic obliquity was heightened in individuals with TFA compared to their healthy counterparts.[16] However, to our knowledge, although dynamic pelvic kinematics have been subject to inquiry in existing literature, there remains a scarcity of studies examining static pelvic tilts. Static PT is important for posture and posture assessments and, together with dynamic PT, provides crucial information in clinical practice and rehabilitation processes. In addition, static PT significantly impacts the fit and use of prostheses in TFP users. Accurate assessment of a patient's pelvic alignment allows for the creation of a more effective and targeted rehabilitation program. However, potential changes in pelvic slopes attributable to differences in socket designs remain unclear.

Post-surgery muscle imbalance, different socket designs, and gait and balance issues may potentially induce changes in pelvic mechanics. There is a lack of studies in the literature that examine alterations in static pelvic tilts resulting from prosthesis utilization. This study aims to investigate PT angles in patients with transfemoral prostheses, considering different socket designs, and to compare these angles with those of healthy controls. The hypothesis suggests that pelvic tilt angles will differ among patients with transfemoral prostheses, regardless of socket type, and will also differ from those observed in healthy subjects. This study, focusing on static PT, aims to fill the gap in the literature regarding this relatively underexplored area compared to dynamic pelvic kinematics. Additionally, it will contribute to a better understanding of the role of pelvic alignment in the process of prosthesis fitting and alignment, particularly in terms of posture assessments and rehabilitation. By providing further insight into how socket design influences static PT and prosthesis use, it will offer practical implications for clinical applications and rehabilitation strategies.

METHODS

Study Design and Participants

This cross-sectional investigation transpired from January 2022 to December 2023. Ethical approval was obtained from the KTO Karatay University Faculty of Medicine Non-medicine and Medical Device Researches Ethics Committee (Date: 20.12.2021, Decision No: 2021/006). Adherence to ethical principles was ensured throughout the study, following the guidelines stipulated by the Declaration of Helsinki. Study participants received comprehensive information about the research, and their participation was contingent upon the acquisition of written informed consent. A total of 28 male volunteers, consisting of TFP users (prosthesis group, n=14) and healthy subjects of similar age and body-mass index (BMI) (control group, n=14), participated in the study.

Participants were aged 18 years or older, had no history of surgeries affecting pelvic mechanics (e.g., lower back, pelvis, or hip), and volunteered willingly. The prosthesis group consisted of individuals with at least one year of unilateral transfemoral prosthesis use. Exclusion criteria included inability to cooperate, history of surgeries, fractures, or musculoskeletal conditions impacting pelvic mechanics, high BMI (BMI ≥35) hindering anatomical landmark identification, and, for the prosthesis group, prosthesis use at any level other than transfemoral.

Pelvic Tilt Measurement

In the sagittal plane, PT was measured using a digital inclinometer (baseline evaluation instruments, white plains, NY, USA) attached to a two-arm caliper. Participants stood with feet shoulder-width apart (approximately 30 cm), with arms either crossed over the chest or extended sideways to prevent interference. Weight was distributed evenly, and potential hip rotations were controlled. The evaluator palpated the PSIS and ASIS, positioning the caliper arms on these landmarks with assistance from a physiotherapist or orthotic-prosthetic technician. Inclinometer readings were recorded and repeated for the opposite side.[18] Lateral pelvic tilt (LPT) in the frontal plane was measured with the caliper arms over the ASISs, and inclinometer values recorded (**Figure 1A, B**). APT is defined as PSIS higher than ASIS, while PPT is the reverse; LPT is identified when one ASIS is higher than the other. This reliable, valid, and cost-effective method is commonly used for assessing pelvic asymmetry.[19] All measurements were conducted by a single, experienced musculoskeletal clinician and researcher.

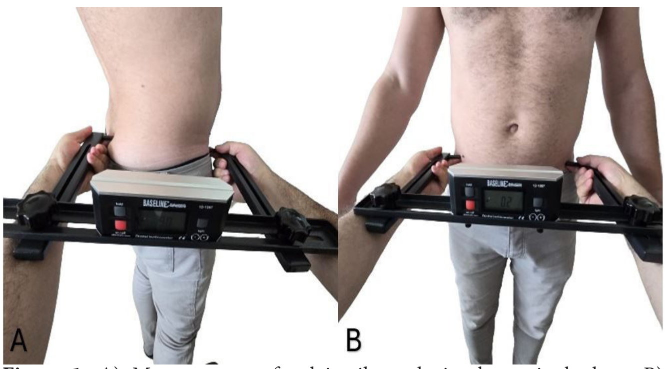

Figure 1. A) Measurement of pelvic tilt angle in the sagittal plane, B) Measurement of pelvic tilt angle in the frontal plane

Statistical Analysis

Data analysis was conducted using SPSS 25 (IBM Inc., Armonk, NY, USA), and sample size was determined with G* Power software. A pilot test with 10 volunteers (5 prosthesis group, 5 control group) was performed to estimate the required sample size. A power analysis based on the pilot study indicated an α level of 0.05, power of 0.95, and ES of 1.46, suggesting a minimum of 14 participants per group.

Descriptive statistics, including mean, standard deviation, median, and quartiles, were presented for both categorical and continuous variables. Variance homogeneity was assessed with the Levene test, and normality was verified using the Shapiro-Wilk test. Since APT and LPT values among all prosthesis users followed a normal distribution, within-group differences were analyzed via paired samples T test. For quadrilateral and ICS socket groups, due to small sample sizes, the Wilcoxon test was used. ESs were calculated using Cohen's d for parametric cases and $r=Z/\sqrt{N}$ otherwise. For independent group comparisons, the independent T test or Mann-Whitney U test was applied as appropriate, with $p<0.05$ considered statistically significant.

RESULTS

Participants

The study included 14 patients with unilateral TFP (mean age: 41.64±14.15 years) and 14 healthy subjects of similar age and BMI (mean age: 42.79±10.30 years). Seven of the patients using TFP were using a quadrilateral socket design, while the other seven were using an ICS design. The duration of prosthesis use was similar between these patients (p=0.949). Two females using TFP were excluded from the study because the pelvic structure in women is different from that in male and there was no possibility of numerical comparison. Additionally, two patients with knee disarticulation were excluded due to potential biomechanical factors that could impact the study outcomes. Participant demographics, including mean age, BMI, and comparisons based on groups and prosthesis usage duration in the TFP group, are detailed in Table 1.

Table 1. Demographic characteristics of the participants

	Total (n=28)	Prosthetic group (n=14)	Control group (n=14)	p
	Mean±SD	Mean±SD	Mean±SD	
Age (years)	42.21±12.16	41.64±14.15	42.79±10.30	0.809[a]
BMI (kg/m²)	26.45±3.91	26.44±4.13	26.46±3.82	0.989[a]
Prosthesis usage time (months)	-	176.57±141.84	-	-

SD: Standard deviation, BMI: Body-mass index, [a]Independent two group T test, p<0.05 bold statistically significant differences

Among the TFP users, 8 (57.1%) and 6 (42.9%) employed prostheses on the right and left extremities, respectively. Detailed information about the prostheses utilized by patients in the prosthesis group and the underlying reasons for amputation are provided in Table 2.

Comparison of PT Angles in the Prosthesis Group

All participants had APT and there was no significant difference in APT and LPT angles between the prosthetic side and the contralateral side in the prosthesis group (p=0.106, effect size (ES)=0.464; p=0.055, ES=-0.564, respectively).

There was no significant difference in APT and LPT angles between the prosthetic side and the contralateral side of the participants using both quadrilateral socket designs and ICS designs (p=0.499, ES=-0.256; p=0.128, ES=-0.575; p=0.063, ES=-0.703; p=0.612, ES=-0.192, respectively) (Figure 2).

Comparison of PT angles between groups

The right APT, left APT, and LPT angles were observed to be higher in the prosthesis group compared to the control group (p=0.001, ES=-0.582; p<0.001, ES=-0.635; p<0.001, ES=-0.797, respectively) (Table 3).

Table 2. Information about the prostheses used by the patients

Prosthetic side	Cause of amputation	Type of socket	Type of suspension	Type of knee	Type of foot	Walking aid	Prosthesis usage time (months)
Left	Firearm injury	Quadrilateral	Pin lock system	Mechanical knee	Single axis foot	No	72
Left	Firearm injury	ICS	Passive vacuum	Pneumatic knee	Carbon foot	No	144
Right	Vascular diseases	Quadrilateral	Pin lock system	Mechanical knee	Single axis foot	No	42
Left	Traffic accident	ICS	Pin lock system	Microprocessor knee	Carbon foot	No	120
Right	Vascular diseases	Quadrilateral	Pin lock system	Mechanical knee	SACH foot	No	24
Right	Traffic accident	Quadrilateral	Suction	Microprocessor knee	Carbon foot	No	384
Left	Firearm injury	ICS	Passive vacuum	Microprocessor knee	Carbon foot	No	180
Left	Firearm injury	ICS	Pin lock system	Microprocessor knee	Hydraulic prosthetic foot	No	324
Right	Firearm injury	Quadrilateral	Active vacuum	Microprocessor knee	Hydraulic prosthetic foot	Yes	468
Right	Osteosarcoma	ICS	Pin lock system	Pneumatic knee	Carbon foot	No	18
Right	Burn	Quadrilateral	Suction	Mechanical knee	Single axis foot	Yes	72
Right	Traffic accident	Quadrilateral	Suction	Microprocessor knee	Carbon foot	No	300
Right	Firearm injury	ICS	Suction	Microprocessor knee	Carbon foot	No	204
Left	Traffic accident	ICS	Passive vacuum	Microprocessor knee	Carbon foot	No	120

ICS: Ischial containment socket

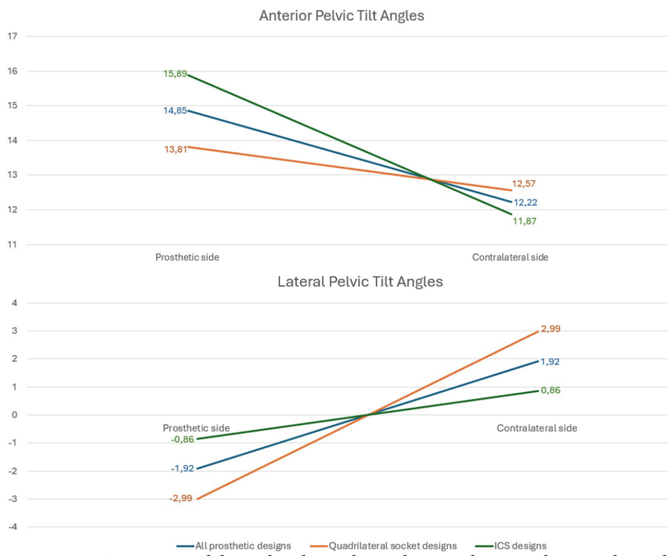

Figure 2. Anterior and lateral pelvic tilt angles on the prosthetic side and contralateral side

Table 3. Comparison of APT and LPT values between groups

	Prosthetic group (n=14)	Control group (n=14)			
	Mean±SD M (IQR 25-75)	Mean±SD M (IQR 25-75)	z	p	Effect size
Right APT (°)	12.79±4.31 13.8 (7.975-16.225)	7.42±1.74 7.20 (6.275-9.325)	-3.079	0.001[a]	-0.582
Left APT (°)	14.29±6.76 13.9 (8.825-17.850)	7.27±1.78 7 (6.100-9.400)	-3.360	<0.001[a]	-0.635
LPT (°)	3.14±2.23 2.75 (1.400-4.625)	0.21±0.15 0.20 (0.100-0.325)	-4.218	<0.001[a]	-0.797

APT: Anterior pelvic tilt, LPT: Lateral pelvic tilt, SD: Standard deviation, M: median, IQR: Interquartile range, p<0.05 bold, statistically significant differences, [a]Mann-Whitney U test, Effect sizes were calculated using the r=Z/√N formula

DISCUSSION

This study examined PT angles in transfemoral prosthesis (TFP) users with different socket designs, comparing them to healthy controls. No significant differences were observed between the prosthetic and contralateral sides or between quadrilateral and ICS socket designs. However, the prosthesis group showed significantly higher right APT, left APT, and LPT angles than controls. Although the APT angle on the prosthetic side was 2.63° higher and LPT was 1.92° lower, these differences did not reach statistical significance. Herrington[3] identified the smallest detectable difference (SDD) in pelvic tilt as 2.5° in asymptomatic individuals, suggesting that our findings may reflect clinically relevant differences despite the lack of statistical significance. Clinically, elevated APT in prosthesis users may lead to back pain, balance and posture issues, and may impact prosthesis fit and duration of use.

Significant differences between the TFP and control groups in right APT (5.37°), left APT (7.02°), and LPT (2.93°) angles suggest that pelvic asymmetry may stem from muscle imbalances due to amputation. Muscle loss, particularly in the hamstrings, quadriceps femoris, and adductor magnus, affects lower extremity control.[20] Post-surgery, residual stumps often move into abduction, altering PT angles on the prosthetic side.[21] Other factors influencing asymmetry include prosthesis lengths,[22] alignment, and soft tissue condition proximal to the stump. Furthermore, it has been reported that stump length is among the factors influencing pelvic asymmetry.[23] The adductor magnus, crucial for thigh stabilization, loses substantial function post-amputation, potentially leading to femoral abduction, whereas knee disarticulation that preserves this muscle can maintain femoral alignment.[20]

Limited studies address static pelvic asymmetry in TFP users, despite extensive research on dynamic pelvic kinematics. Gaunaurd et al.[22] identified asymmetry in the pelvic innominate slope in TFP users, but their study included more male participants, knee disarticulation cases, and had a larger sample. Our smaller sample, excluding females and knee disarticulation cases, may explain the lack of significant findings. Increased sample size might yield significant results.

Socket designs can affect the contraction strength and function of the muscles within the socket. Socket designs that keep the femur in an adducted position help the hip abductors to stabilize the pelvis and reduce compensatory movements associated with the pelvis and trunk.[21] Prior research suggested quadrilateral sockets might limit frontal-plane pelvic movement, but the small sample size limited interpretation.[24] In our study, socket type did not significantly affect pelvic asymmetry, though larger sample sizes may clarify these findings. An alternative to traditional socket-based systems is osseointegration prostheses, which eliminate the need for a socket entirely. These prostheses may influence pelvic mechanics differently by enabling more natural muscle activation and direct load transfer through the femur. They have been associated with improvements in comfort and functional mobility, potentially reducing compensatory movements and asymmetries. Studies have shown that osseointegration prostheses for transfemoral amputees can significantly improve walking parameters, quality of life, and prosthesis use compared to socket prostheses.[25,26] Additionally, these prostheses offer better stability, reduced pain, and fewer skin problems at the stump/socket interface. However, complications such as infections and the need for additional surgeries are notable challenges.[25] Further research comparing osseointegration systems with conventional socket designs could provide valuable insights into their distinct effects on pelvic mechanics.

Our hypothesis that PT angles would be different in patients using TFP regardless of socket type was not realized. This discrepancy may be attributed to the limited number of TFP users and heterogeneity in the duration of prosthesis use. Nonetheless, our second hypothesis, positing different PT angles in TFP users and healthy individuals, was affirmed.

Limitations

Several limitations were identified in the study. Firstly, the stump length in prosthesis patients was not measured, and its potential impact on prosthetic control and pelvic stability was not investigated. Stump length is considered a critical parameter and may play a role in these aspects. Secondly, the prosthesis use durations were not homogeneous. The duration of prosthesis use may influence changes in PT angles. Over time, muscle atrophy, hypertrophy, and habitual walking patterns may contribute to changes in PT. Furthermore, although a pilot study was conducted to guide participant recruitment, a larger cohort would have allowed for a more robust interpretation of the results. Finally, the insufficient representation of females in the prosthesis group (only 2 out of 16 patients were female) limited the opportunity for gender-specific comparisons.

CONCLUSION

Among patients with TFP, no statistically significant differences in PT angles were observed between the prosthetic side and the contralateral side in both the sagittal and frontal planes. However, a significant difference in these angles was found when comparing prosthetic patients to healthy controls. Differences in pelvic tilt angles are likely to lead to orthopedic dysfunctions such as low back pain, muscle imbalance and socket alignment problems over time. Further studies should focus on the presence of these problems in TFP users.

ETHICAL DECLARATIONS

Ethics Committee Approval

Ethical approval was obtained from the the KTO Karatay University Faculty of Medicine Non-medicine and Medical Device Researches Ethics Committee (Date: 20.12.2021, Decision No: 2021/006).

Informed Consent

Informed consent was obtained from all patients for being included in the study.

Referee Evaluation Process

Externally peer-reviewed.

Conflict of Interest Statement

The author has no conflict of interest to declare in relation to this article.

Financial Disclosure

The author declares that this study has received no financial support.

Author Contributions

All of the authors declare that they have all participated in the design, execution, and analysis of the paper, and that they have approved the final version.

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