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ORIGINAL ARTICLE

Dynamic Plantar Pressure Patterns and Their Role in Optimizing Energy Transfer During the Golf Swing

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ABSTRACT

Background. Transferring energy from the lower extremities to the torso is a crucial mechanism enabling an effective golf swing. However, the optimal plantar pressure distribution that facilitates this energy flow has not been thoroughly investigated. **Objectives.** This study explored the relationship and predictive potential between peak in-shoe plantar pressures at specific locations and the mechanical energy flow to the torso region during the golf swing. **Methods.** Thirty amateur golfers, each with a handicap between 0 and 15, participated in this study. This range represents golfers with moderate skill levels, including highly skilled amateurs (closer to 0) and intermediate players (closer to 15). Plantar pressure distribution was recorded with instrumented insoles, and torso energy flow was measured using a 3D motion analysis system and force plate. Stepwise regression analysis identified pressure locations contributing to energy transfer ($p<0.05$). **Results.** Peak plantar pressures at the right medial metatarsal ($\beta=1.75$, $t=4.31$, $p=0.001$) and left lateral arch ($\beta=1.35$, $t=2.22$, $p=0.048$) were positively linked to trunk energy transfer, while left great toe pressure ($\beta=-20.06$, $t=-4.51$, $p=0.001$) showed a significant negative correlation. The regression model had an R^2 of 0.80. **Conclusion.** The findings suggest optimal plantar pressure supports efficient energy transfer, while pressure in unfavorable locations may hinder swing efficiency.

INTRODUCTION

The golf swing represents one of the most sophisticated and demanding biomechanical movements within the sporting domain (1). An effective golf swing necessitates synchronizing various body parts to produce and transmit kinetic energy to the clubhead, ultimately influencing clubhead speed and ball flight distance. Proper weight transfer, specifically shifting body mass during the swing, is a crucial factor in this process (2). Recent research has highlighted the influence of various factors on golf swing performance, including the role of ground reaction force (3), the interplay of linear and angular momentum (4), and the significance of physical conditioning (5).

Previous research has demonstrated the importance of weight transfer patterns and center of pressure (COP) location concerning clubhead speed (6, 7). Skilled golfers generally exhibit greater COP displacement, characterized by increased weight shift towards the front foot and reduced loading on the rear foot prior to impact (7). Ball and Best (8) identified two distinct swing patterns: "Front Foot," where weight is transferred to the front foot through impact, and "Reverse," where weight shifts back toward the rear foot near impact. These patterns have been further explored in studies examining the impact of different swing styles and club types on COP trajectories (5).

However, these studies primarily focus on overall COP movement, which may not fully capture nuanced variations in pressure distribution across specific areas of the foot. Plantar pressure distribution has been suggested as a valuable measure to provide more detailed insights into localized pressure patterns during the swing, potentially influencing energy generation and transfer. Pataky (9) found a positive correlation between clubhead speed and pressure on the lateral side of the leading foot, suggesting that weight transfer location, not just the amount of transfer, may be a critical factor. Similarly, Worsfold et al. (10) supported that plantar pressure distribution can influence clubhead speed. The role of plantar pressure distribution in golf swing biomechanics has been further investigated in a recent study (11), which utilized the Hilbert-Huang transform to analyze golf swing motion and identify movements associated with different ball trajectories.

Despite some research examining plantar pressure distribution, most studies have emphasized static measurements and lack in-depth analysis of dynamic mechanical energy flow within the body. Recent studies have highlighted the importance of examining segment kinetic energy to explore sequential movements and ground reaction forces in enhancing swing technique and performance (12, 13). For instance, Outram and Wheat (12) investigated the reliability of segment kinetic energy measures in the golf swing. Belotti et al. (13) explored the impact of foot proprioception training on ground reaction forces and swing performance. These studies underscore the need for a more comprehensive understanding of how plantar pressure dynamics contribute to energy transfer and overall swing efficiency. Understanding how foot loading patterns influence energy flow through different body segments, particularly the trunk, which serves as a conduit for energy transfer from the lower to the upper body, remains a key area requiring further investigation. This study addresses this gap by investigating the correlation between dynamic plantar pressure distribution and energy transfer in the golf swing, utilizing a comprehensive approach that incorporates kinetic and kinematic analyses.

This study investigates the correlation between plantar pressure distribution and mechanical energy flow in the trunk during the golf swing. By analyzing data at a localized level within the foot, this research seeks to understand the role of specific plantar pressure patterns in facilitating energy transfer from the lower body to the trunk, focusing on a cohort of 30 golfers with handicaps ranging from 0 to 15. Unlike previous studies that primarily focused on the overall center of pressure movement, this study provides a more nuanced understanding of swing mechanics by examining localized plantar pressure patterns and their dynamic relationship with energy transfer. The findings will contribute to a deeper understanding of swing mechanics and energy transfer in golfers of varying skill levels.

MATERIALS AND METHODS

Participants. A priori power analysis using G*Power software was conducted to determine the appropriate sample size for this multiple linear regression study. The analysis aimed for a power of 0.80 with an alpha error probability of 0.05, using an effect size (R square) of 0.60 based on similar previous research (9). This analysis indicated a minimum required sample size of 23 participants.

This study (EC-67-152) received ethical approval from the Suranaree University of Technology, and all participants gave informed consent before participating. Participants wore their appropriate athletic attire and used their clubs for our measurements. Thirty golfers with handicaps ranging from 0 to 15 participated in the study, comprising 15 male and 15 female golfers. Hand dominance was determined by asking each participant which hand they used for golfing. This study had specific inclusion and exclusion criteria. Participants were considered for inclusion in this study if they had a handicap ranging from 0 to 15, had no history of lower extremity or spine musculoskeletal injuries in the past 6 months, and were right-hand dominant. Participants were excluded from this study if they had a history of lower extremity or spine musculoskeletal injuries in the past 6 months or were left-hand dominant. The individual characteristics of the participants are summarized in Table 1, which outlines the descriptive statistics for key participant characteristics, comprising the demographic attributes of age, weight, height, and body mass index (BMI).

Table 1. Statistical Description of Individual characteristics.

Variables	M ± SD
Age (years)	24.20 ± 4.74
Weight (kg)	75.80 ± 20.00
Height (cm)	170.60 ± 5.41
BMI (kg/m^2)	25.83 ± 5.96

M: Mean; SD: Standard Deviation; BMI: Body Mass Index.

Data Collection. All participants wore appropriate sports attire and used their familiar driver golf clubs during the plantar pressure and energy transfer measurements. The analysis focused on the period surrounding ball impact. Participants were equipped with 42 reflective markers placed on anatomical landmarks of the body and the club. The markers were placed according to the Qualisys Sports Marker Set (14). Body and club movement during the golf swing was captured using six motion capture cameras (Oqus 7+ series, Qualisys AB, Sweden) at a sampling rate of 200 Hz. Ground reaction forces were measured for each foot using two force platforms (Kistler 9286BA, Kistler Group, Switzerland) at 1500 Hz. Plantar pressure distribution was recorded using insole sensors (Surasole Pro 8, Suratec Co., Ltd., Nakhon Ratchasima, Thailand). The insoles contained eight resistive sensors embedded within each insole, strategically positioned to capture pressure variations across the foot. Data collected during the trials was segmented into eight-foot areas, as shown in Figure 1. These sensors interfaced with a microcontroller via a voltage divider circuit, with the output connected to a 10-bit analog-to-digital converter. The circuit was calibrated for each sensor to operate within a full-scale force range (0-20 kg) and had a response time of less than 10 microseconds, sampled at 20 Hz.

The researchers utilized Visual3D software (C-Motion, Germantown, MD) to compute joint forces and moments, employing a comprehensive full-body model comprising 14 segments and 26 degrees of freedom. Segmental power analysis for the trunk segment was employed to quantify the energy flow (15). Joint force power (JFP), segment torque power (STP), and segment power (SP) were calculated as follows:

$$JFP = (F_j) \bullet (V_j)$$

$$STP = \left(T_j\right) \bullet (\omega_s)$$

$$SP = JFP_d + JFP_p + STP_d + STP_p$$

Where F_j is the joint reaction force, V_j is linear joint velocity, T_j is the joint moment, and ω_s is segment angular velocity. To assess energy transfer, the rate of energy flow out of or into a body segment (SP) is the combination of joint force power (JFP) and segment torque power (STP), with d and p referring to the distal and proximal joints of the segment, respectively (16-19).

Following equipment setup, participants completed a 10-minute warm-up to acclimate to the equipment. All measurements were performed by the same researcher throughout the study to ensure consistency in data collection. This individual was responsible for fitting participants with instrumented insoles, calibrating the motion capture system, and supervising data collection. Each participant's golf swing was assessed using standardized biomechanical protocols to ensure accuracy and reliability in measurement. During data collection, participants performed five golf swings, replicating competitive conditions for each swing. A one-minute rest period was provided between swings. Upon completion of testing, participants engaged in a 10-minute cool-down involving stretching exercises.

Statistical Analysis. Data from the five recorded swings of each participant were analyzed using stepwise multiple linear regression to identify significant predictors of total energy flow at the lumbosacral joint (L5S1). This method sequentially adds independent variables to the regression equation based on their correlation with the dependent variable. The significance of each variable in the equation is continuously evaluated, and non-significant variables are removed. Before analysis, the assumptions of linear regression were assessed, including data independence, normality of residuals, linearity of the relationship, and homoscedasticity. All statistical analyses were performed using SPSS 26.0 software (IBM Corporation, Somers, NY, USA).

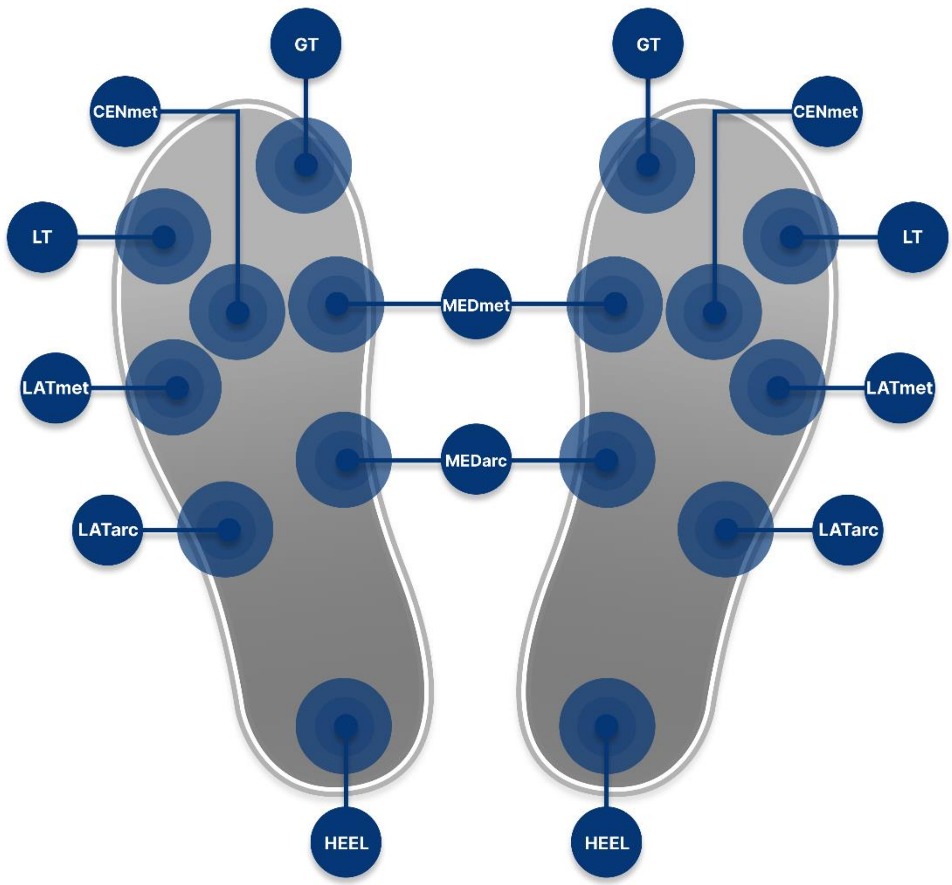

Figure 1. The eight plantar regions analyzed in the statistical investigation were: great toe (GT), lesser toe (LT), medial metatarsal (MEDmet), central metatarsal (CENmet), lateral metatarsal (LATmet), medial arc (MEDarc), lateral arc (LATarc), heel (HEEL).

RESULTS

Examination of the peak in-shoe plantar pressure patterns observed during the impact phase of the golf swing demonstrated distinct distributions across the eight defined sensor regions on each foot. Locations significantly correlated with energy flow are highlighted by a star symbol to indicate their predictive influence, as shown in Figure 1. The analysis revealed peak plantar pressures at the right foot's medial metatarsal (85.19 ± 49.52 kPa) and the lateral arch of the left foot (50.07 ± 32.93 kPa). Notably, the left great toe region exhibited significantly lower pressure than the other areas (Table 2).

Energy transfer at the lumbosacral joint (L5S1) reaches its peak during the downswing to impact transition, as illustrated in Figure 2. This peak signifies the effective transfer of energy from the lower body to the trunk, facilitated by optimal plantar pressure distribution between both feet. Conversely, imbalances or improper plantar pressure distribution can negatively impact energy transfer. As shown in Figure 3, pressure patterns that deviate from efficient movement mechanics may diminish the energy transferred to the trunk, hindering the generation of a smooth and powerful swing.

Table 2. Mean and standard deviation of plantar pressure for eight areas on each foot during ball impact.

Areas	Left foot (kPa)	Right foot (kPa)
	M ± SD	M ± SD
Great Toe (GT)	17.56 ± 4.35	70.57 ± 32.21
Lesser toe (LT)	19.36 ± 2.73	21.08 ± 13.38
Medial Metatarsal (MEDmet)	36.49 ± 22.67	85.19 ± 49.52
Central metatarsal (CENmet)	41.89 ± 11.58	12.59 ± 9.65
Lateral Metatarsal (LATmet)	65.61 ± 22.74	13.96 ± 8.94
Medial Arc (MEDarc)	22.64 ± 23.03	22.89 ± 12.21
Lateral Arc (LATarc)	50.07 ± 32.93	13.16 ± 9.18
Heel (HEEL)	36.09 ± 21.84	19.44 ± 10.55

M: Mean; SD: Standard Deviation.

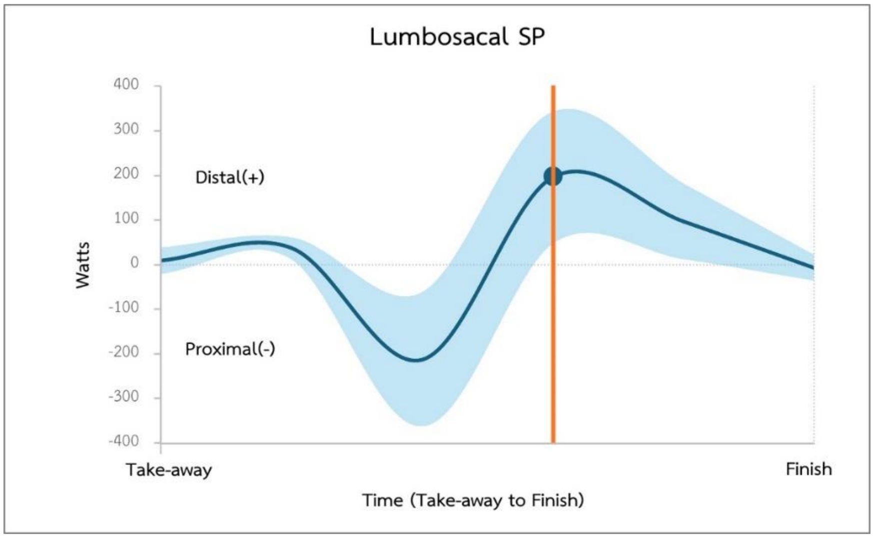

Figure 2. Average energy flow at lumbosacral joint (L5S1) during the golf swing, the impact point indicated by an orange vertical line to highlight this critical moment.

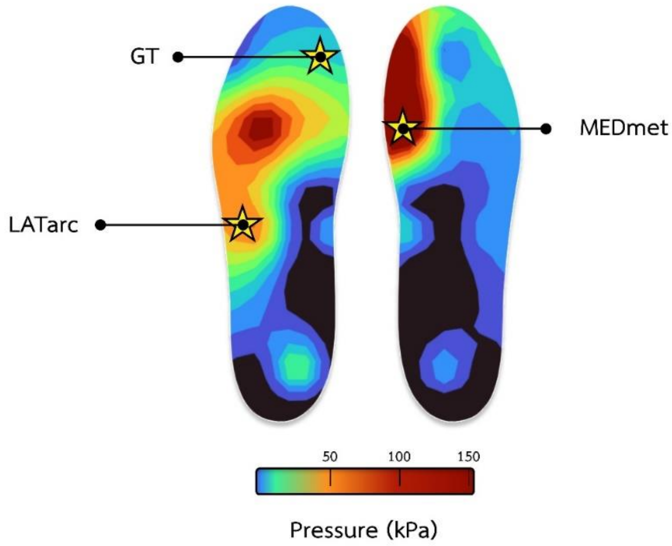

Figure 3. Average maximum plantar pressure distribution across different foot areas during the golf swing at ball impact.

Analysis of the relationship between plantar pressure and mechanical energy transfer at the lumbosacral joint (L5S1) using stepwise multiple linear regression revealed that pressure in the medial metatarsal of the right foot (β = 1.75, t = 4.31, p = 0.001) and the lateral arch of the left foot (β = 1.35, t = 2.22, p = 0.048) was positively associated with energy transfer, while pressure in the left great toe region (β = -20.06, t = -4.51, p = 0.001) was negatively associated. The model had a coefficient of determination (R^2 = 0.799), indicating that these variables accounted for 79.9% of the variance in energy transfer (Table 3).

Table 3. Relationship and predictive ability of the segmental power (SP) at the lumbosacral joint (L5S1) during ball impact.

Variable		Beta Coefficient	t-value	p-value
Constant		331.68	3.41	0.006†
Left foot	**GT**	-20.06	-4.51	0.001†
Left foot	**LATarc**	1.35	2.22	0.048*
Right foot	**MEDmet**	1.75	4.31	0.001†
R^2			0.80	

R^2: Coefficient of Determination; *: Significant at $p < 0.05$; †: Significant at $p < 0.01$.

DISCUSSION

This study examined the relationship between the peak plantar pressures measured within the shoes and mechanical energy flow in the trunk during the golf swing in 30 golfers with handicaps ranging from 0 to 15. The findings highlight the significant role of plantar pressure distribution in supporting energy transfer, aligning with biomechanical principles that suggest optimal pressure distribution enhances efficient movement (1, 20).

The study's results revealed that appropriate plantar pressure distribution plays a crucial role in supporting energy transfer from the lower body to the trunk, especially during key stages of the golf swing, such as the impact event. This process aligns with the concept of kinetic linking, which underscores the sequential energy transfer through body segments (21). These findings are consistent with previous studies by Ball and Best (2, 6, 8), which demonstrated that proper movement of the center of pressure (COP) enhances torque and driving forces necessary for generating clubhead speed. Additionally, recent research (22) has explored the influence of uphill and downhill slopes on COP movement and shot outcomes, further emphasizing the importance of COP control in dynamic swing conditions.

Conversely, imbalanced pressure distribution, such as excessive pressure in certain regions, may reduce energy transfer efficiency. This inefficiency can result from mechanical compensations, such as diminished torque at the hip or lumbosacral joints (1, 9). This study also supports the findings of Bradshaw et al. (23), who noted that golfers with abnormal plantar pressure patterns often experience difficulties in controlling movement consistency and maintaining swing efficiency. Furthermore, a recent study (24) investigated the relationship between skill and ground reaction force variability in amateur golfers, highlighting the impact of inconsistent plantar pressure patterns on overall swing variability.

This research underscores the importance of plantar pressure distribution in energy transfer during the golf swing. Proper pressure distribution enhances movement efficiency and significantly reduces the risk of injury, particularly in the lower back, a common issue among golfers (25, 26). This finding provides a reassuring insight into the potential for injury prevention in the sport. Recent research has also explored the role of various factors in golf-related injuries, including swing biomechanics and physical conditioning (5, 25).

Moreover, these findings can inform the development of golf-specific footwear and assistive devices that optimize plantar pressure distribution. As sports scientists, golf coaches, and footwear designers, your role in applying these findings to design insoles that enhance pressure distribution or implement training routines focusing on proper weight transfer is crucial. This application could significantly improve swing efficiency and mitigate injury risks for golfers.

This study investigated the relationship between plantar pressure and energy transfer in golfers with handicaps of 0-15 (15 male, 15 female) using the Modern swing. While this study design allows for a focused analysis, it also presents certain limitations. Our findings' generalizability may be limited as the sample does not encompass golfers with higher handicaps, different swing styles, or diverse physical characteristics. Future research could include a broader array of golfers to enhance the universality and comparability of the findings. Additionally, this study did not explicitly examine the influence of individual differences in foot morphology, which can affect plantar pressure patterns and energy transfer. Further research is needed to explore how variations in foot morphology impact these variables.

CONCLUSION

This investigation contributes to a more profound comprehension of the underlying mechanisms governing energy transfer during the golf swing by emphasizing the pivotal role of plantar pressure distribution in enabling balanced and efficient movement patterns. The findings offer valuable applications for research, sports equipment development, and training strategies to improve performance and reduce injury risks for golfers across all skill levels. Specifically, these findings can inform the design of future longitudinal studies investigating the long-term effects of plantar pressure training on swing performance and injury prevention. Furthermore, the results can guide the development of targeted interventions, such as personalized footwear or orthotics, to optimize plantar pressure distribution and enhance energy transfer during the golf swing.

APPLICABLE REMARKS

- Integrating plantar pressure assessment and energy transfer evaluation can provide insights into how pressure distribution influences the energy transfer through the kinetic chain during the golf swing.
- Golf footwear design should incorporate findings on optimal plantar pressure zones to enhance stability and efficiency while mitigating injury risks.
- Training programs should focus on balancing plantar pressure during key swing phases to improve kinetic chain efficiency and swing consistency.

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AUTHORS' CONTRIBUTIONS

Study concept and design: Khemchat Chaemklan, Pornthep Rachnavy. Acquisition of data: Khemchat Chaemklan. Analysis and interpretation of data: Khemchat Chaemklan. Drafting of the manuscript: Khemchat Chaemklan, Dipak Kumar Agrawal. Critical manuscript revision for important intellectual content: Khemchat Chaemklan, Pornthep Rachnavy, Dipak Kumar Agrawal. Statistical analysis: Khemchat Chaemklan. Administrative, technical, and material support: Pornthep Rachnavy, Soodkhet Pojprapai. Study supervision: Khemchat Chaemklan, Pornthep Rachnavy, Soodkhet Pojprapai.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FINANCIAL DISCLOSURE

The authors have no financial interests related to the materials in the manuscript.

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ETHICAL CONSIDERATION

This study was approved by the Human Research Ethics Committee of the Suranaree University of Technology (Project code: EC-67-152). Informed consent was obtained from all participants involved in this study.

ROLE OF THE SPONSOR

The funding organizations are public institutions and have no role in the study design, data collection, data analysis, interpretation of results, manuscript preparation, or decision to submit the article for publication.

ARTIFICIAL INTELLIGENCE (AI) USE

Artificial intelligence tools were not utilized in this manuscript's conceptualization, data analysis, or writing, except for general-purpose language models used for proofreading or editing assistance, where applicable.

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