ÓBUDAI EGYETEM
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DOCTORAL (PhD) THESIS BOOKLET

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Stiffness-related coupling analysis of the biomechanical functions of the human foot-ankle complex

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Table of Contents

1 Summary in Hungarian Language

A lábboltozat merevségének szabályozásával a lábboltozat rugalmassága javíthatja a járás hatékonyságát a mechanikai energia tárolása és visszanyerése révén. A boltívben lévő szövetek merevségének köszönhetően a csörlő mechanizmus a metatarsophalangealis dorsiflexió közben a talpi izompólyát a lábközépcsont feje körül feltekeri, ezáltal lerövidíti és megemeli a boltívet, és megfordítja a subtalaris ízületet. Figyelembe véve a megváltozott metatarsophalangealis kinematika hatását a talpi izompólya törzsre, a boltív-rugó mechanizmus tovább emeli a szalagos struktúrák jelentős hozzájárulását a rugalmas energiaelnyeléshez és -disszipációhoz.

A morfológiai evolúció és a funkcionális adaptáció révén a lábboltozat szerkezeti változásai elkerülhetetlenül az alsó végtagok biomechanikájának változásaihoz vezetnek.

A jelen munka a láb-boka komplex biomechanikai funkcionális analízisét és végeselem-elemzését kombinálta, hogy feltárja a lábfejre jellemző a mozgás közbeni boltívmerevséggel kapcsolatos funkcionális mechanizmusokat. A morfológiai boltív biomechanikai funkciójának megértése további hasznosítható ismereteket nyújthat a lábsérülések előrejelzése és az alsó végtag ízületeinek mozgás közbeni átfogó kompenzációs beállítása révén.

A disszertáció lábmorfológiai mérésekkel indult, hogy a felkért alanyok lábboltozat-merevségét osztályozzák a háromdimenziós ívparaméterek számítása alapján különböző terhelési feltételek mellett. Ezután minden alanynak járásteszteket kellett elvégeznie egy szabványos biomechanikai laboratóriumban, beleértve a járást, a futást, a tervezett és nem tervezett járás megszakításokat. A járástesztek kinematikai és kinetikai paramétereit összegyűjtöttük a későbbi mozgásszervi modellezéshez. Statisztikai, nem paraméteres leképezési megközelítést alkalmaztuk az ív merevségének a láb-boka kinematikájára gyakorolt hatásának felmérésére.

Az eredmények azt mutatják, hogy a lábközépcsont és a bokaízület szöge a boltívmerevségnek és a járás mintáknak köszönhetően megváltozott. Ezek az eredmények további betekintést adnak a morfológiai ív biomechanikai funkciójába és az alsó végtag ízületeinek átfogó kompenzációs beállításába a nem tervezett stimuláció okozta járásmegállítás során.

Ezen kívül az ízületek közötti koordinációt és variabilitást a térd-csípő, boka-térd és metatarsophalangealis-boka csatolások szög-szög diagramjaiból számítottuk egy optimalizált vektorkódolási technika alapján. Ezek a megfigyelések azt mutatták, hogy a rugalmas boltívű egyének hajlamosak egy konzervatív koordinációs stratégiát elfogadni, amely jobban működik boltív stabilizátorként és ahjtóerőként az ív-rugó mechanizmuson keresztüli nyújtási-rövidítési ciklus során.

A számítógépes szimulációt illetően reverse engineering technológiát alkalmaztam a vizsgált személy jobb lábának geometriai adatainak beszerzésére és a láb-boka komplex végeselemes modelljének felállítására. A láb végeselemes modelljét a szimulációk és a kísérleti mérések alapján nyert talpi nyomás összehasonlításával tovább validáltuk. A lábközépcsont terhelése csökkenthető a talpi izompólya merevségének beállításával, a lábközépcsontok fáradási károsodása felgyorsulhat, mivel a mediális lábközépcsontok dorsalis részei általában nyomás alatt vannak, és ezekre a csontokra ható hajlítási terhelések megnövekednek az izompólya terhelésének csökkenése révén.

Összefoglalva, ennek a tanulmánynak az eredményei átfogó biomechanikai részleteket és alternatív megközelítéseket kínálhatnak a klinikusok és a kutatók számára az ortopédiai fejlesztés értékeléséhez és optimalizálásához, valamint a merevséggel kapcsolatos lábboltív sérülések kockázatának csökkentéséhez.

2 Antecedents of the Research

A well-functioning foot-ankle structure is significant in daily locomotor tasks [1]. As the primary part for adjusting foot stiffness, the foot arch is springlike, as it compresses during the early stance phase and recoils during the late stance phase, which could improve gait efficiency by storing and returning mechanical work [1-3]. Given the stiffness of arch-spanning tissues, the windlass mechanism indicates that metatarsophalangeal (MTP) dorsiflexion produces the winding of the plantar fascia (PF) about the head of the metatarsus, thereby shortening and raising the arch, and inverting the subtalar joint [4]. On the other hand, considering the impact of altering MTP kinematics on the PF strain, the arch-spring mechanism further emphasizes the significant contribution of ligamentous structures, represented by the PF, to elastic energy absorption and dissipation [1]. Welte et al. [2] investigated the interaction between the above two mechanisms and found that the engagement of the windlass through MTP dorsiflexion reduced arch stiffness (AS), and increased energy storage and return.

MTP dorsiflexion may consequently influence foot movement by adjusting the mechanical energy pattern. Kirsty et al. [5] also found that the PF demonstrated a characteristic elastic stretch-shortening cycle, with most of the strain produced through compressing the arch. The energy transfer mechanism of the PF between the MTP (energy absorption) and the foot arch (energy produced during recoil) reduces the strain required for the PF to produce positive mechanical work at the arch.

From the perspective of morphological evolution and functional adaptation, structural changes in the foot arch will inevitably lead to variations in the lower-limb biomechanics, increasing the potential risk of foot damage and musculoskeletal problems [6-8]. Although arch height is overwhelmingly cited as a predictive factor for podiatry, there is emerging evidence that AS (or arch flexibility) might also be a critical contributor [9]. It is also considered to be a standard for evaluating injury susceptibility considering the association among ground reaction force (GRF), foot pronation/supination, and foot injury [9, 10]. Despite some studies demonstrating links between arch morphological characteristics and discrete biomechanical data, little work has examined the correlation between AS and temporal kinematics. Statistical parametric mapping (SPM) has proven to be helpful in biomechanical data with time-varying characteristics in previous studies [11, 12]. Statistical nonparametric mapping (SnPM), as an SPM nonparametric equivalent, permits hypothetical testing on the whole waveform rather than concentrating on specific data points, thus compensating for regional focus bias [13, 14]. The amplitude of the loading on the arch would further increase in comparison to steady-state gait during gait termination (GT) [15]. Furthermore, the GT task was performed as a valuable tool for gait analysis, and it is widely used to assess motor function in patients with balance disorders [16, 17]. As the closest anatomically to the arch, the biomechanical properties between the MTP and ankle joint are also worth exploring during GT induced by unplanned stimuli.

Another area that has yet to be explored is the implications of AS on lower extremity coupling coordination in gait. Traditional biomechanical gait assessments have typically used discrete measures, such as range of motion (ROM) and peak plantar pressure. Nevertheless, isolated joint kinematics can neither effectively reflect the segmental coordination information producing resultant angular positions nor provide a comprehensive insight into the altered movement patterns caused by functional differences in the foot [18]. A continuous approach, in contrast, enables the quantification of movement coordination patterns throughout the gait cycle and can provide spatial-temporal details of the locomotion [19]. Coupling coordination analysis allows for assessing the timing and magnitude of relative motion between body segments, while coordination variabilities (CVs) further quantify the degree of fluctuation in coordination patterns [18, 19]. While numerous studies have shown relationships between kinematic coupling behavior and arch biomechanical function, and between foot morphology and injury susceptibility, few have investigated the association between lower extremity inter-joint coordination and AS [20, 21].

The etiology of biomechanical metatarsalgia has been recognized as alterations in weight distribution to the MTP joints due to functional or structural changes [22]. Nevertheless, these laboratory-based experimental results may be limited since they cannot allow direct assessment of detailed mechanical changes in the foot structure, particularly for the internal stress and strain distribution in the metatarsal region [23, 24]. To overcome the above-mentioned intrinsic difficulties, computational modeling techniques, represented by the finite element (FE) analysis, provided the feasibility for methodological purposes. Therefore, the present work aimed to combine biomechanical functional analysis and FE analysis of the foot-ankle complex to reveal foot-specific functional coupling mechanisms related to AS during motion. An understanding of the morphological arch biomechanical function may provide additional insights into foot injury prediction and the comprehensive compensatory adjustment of lower-limb joints.

3 Objectives

The first objective: To investigate the foot-ankle temporal kinematic characteristics of stiff- and flexible-arched individuals during planned and unplanned gait terminations (PGT and UGT) using an SnPM method.

The second objective: To examine the influences of AS on the lower extremity segment CVs and anterior-posterior ground reaction impulses (AP-GRIs).

The third objective: To reconstruct a subject-specific FE model of the foot-ankle complex utilizing the exact three-dimensional geometry of foot bone and soft tissue, and examine the influences of PF stiffness on metatarsal stress distribution and joint force transmission.

4 Research Methods and Challenges

Methods: The present work combined biomechanical functional analysis and FE analysis of the foot-ankle complex to reveal foot-specific functional coupling mechanisms related to AS during motion.

The dissertation began with foot morphological measurements to classify the foot AS of recruited subjects based on the calculation of three-dimensional arch parameters under different loading conditions. All subjects were then required to complete gait tests in a standard biomechanical laboratory, including walking, running, PGT and UGT. Kinematic and kinetic parameters from the gait tests were collected to perform the subsequent musculoskeletal modelling. The SnPM approach was employed to assess the impacts of AS on foot-ankle kinematics during PGT and UGT. Inter-joint coordination and variability were calculated from the angle-angle plots of knee-hip, ankle-knee, and MTP-ankle couplings based on an optimized vector coding technique.

Regarding the computational simulation, reverse engineering technology was used to acquire geometrical data of the right foot of the subject and establish a subject-specific FE model of the foot-ankle complex. A sensitivity investigation was conducted to evaluate the effects of varying PF stiffness on the metatarsal stress distribution and joint force transmission. The foot FE model was further validated by comparing plantar pressure acquired from computational simulations and experimental collections.

Challenges: There are some challenges of the present study that need to be acknowledged. Firstly, as an easily-acquired indirect metric, the AS predicts arch deformation during dynamic loading by comparing the adaptation of the arch height between two different static load-bearing conditions. Concerns have been raised that static (complex foot anatomical factors) variables and dynamic (foot neuromuscular control during locomotion) variables may confound the results of the study. Secondly, while the SnPM was effective in ANOVA for biomechanical data with time-varying characteristics, post hoc tests with Bonferroni correction might be relatively approximate and conservative. Lastly, in the current foot FE model, several considerations related to the balance between exact details and proper simplifications (i.e., computational cost) need to be attended to for the predicted results and further practical applications. Additionally, the analysis focused on balanced standing, and future studies should encompass more complex load-bearing phases, requiring further dynamic FE analyses.

5 New Scientific Results

1st Thesis point: I compared foot-ankle temporal kinematics characteristics during PGT and UGT in subjects with different ASs based on the SnPM method (Figure 1).

- The results show that joint angles (MTP and ankle joints) were altered owing to AS and GT factors. These results add additional insights into the morphological arch biomechanical function and the comprehensive compensatory adjustment of lower-limb joints during gait stopping caused by unplanned stimulation.
- As shown in Figure 1, flexible arches exhibit a significantly increased ankle plantarflexion in the sagittal plane during the braking and transitional phases of GT, while external rotation was greater than that of SA during the transitional and stabilization phases.
- Significantly smaller MTP inversion and external rotation angles are exhibited during UGT during braking and transitional phases, which might be an integrated response concerning the MTP-ankle coordination pattern to compensate for increased ankle inversion.

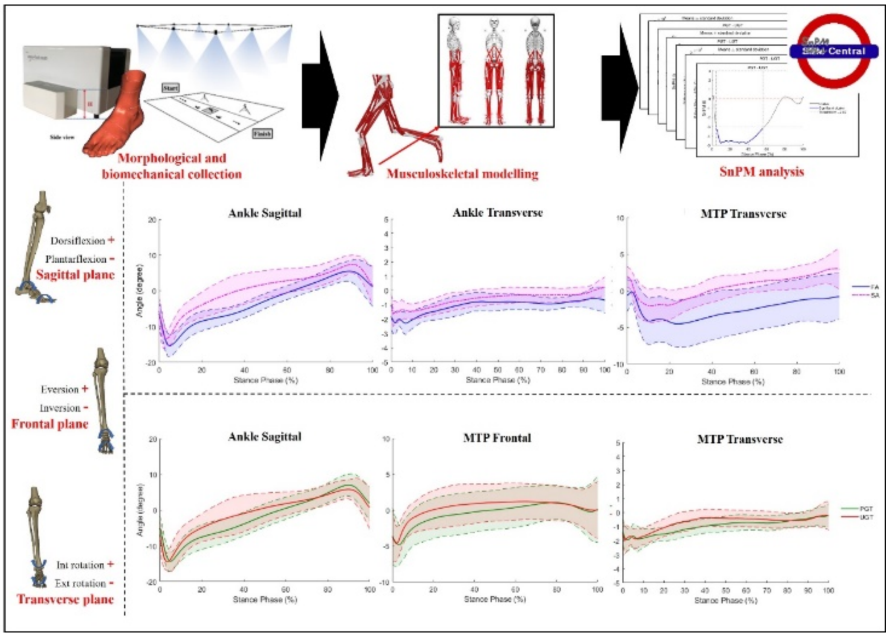

Figure 1 The effect of arch stiffness on the foot-ankle temporal kinematics during gait termination [8.1 Scientific Publications related to the Thesis Points, P1 & P2]

2nd Thesis point: I investigated how the foot structural characteristics, as represented by the AS, affect lower limb joint coupling coordination and AP-GRIs during walking and running. Inter-joint coordination and variability were calculated from the angle-angle plots of knee-hip, ankle-knee, and MTP-ankle couplings based on an optimized vector coding technique (Figure 2).

- The results indicate that coupling coordination of interest and its variability, as well as AP-GRIs, could potentially be influenced due to differences in arch height flexibility.
- Furthermore, combining the SPM analysis results, the flexible arches experienced a greater proportion of GRIs in the AP direction.
- These observations demonstrated that individuals with a flexible arch tend to adopt a conservative coordination strategy that better functions as an arch stabilizer and propeller during the stretch-shortening cycle via the arch-spring mechanism.

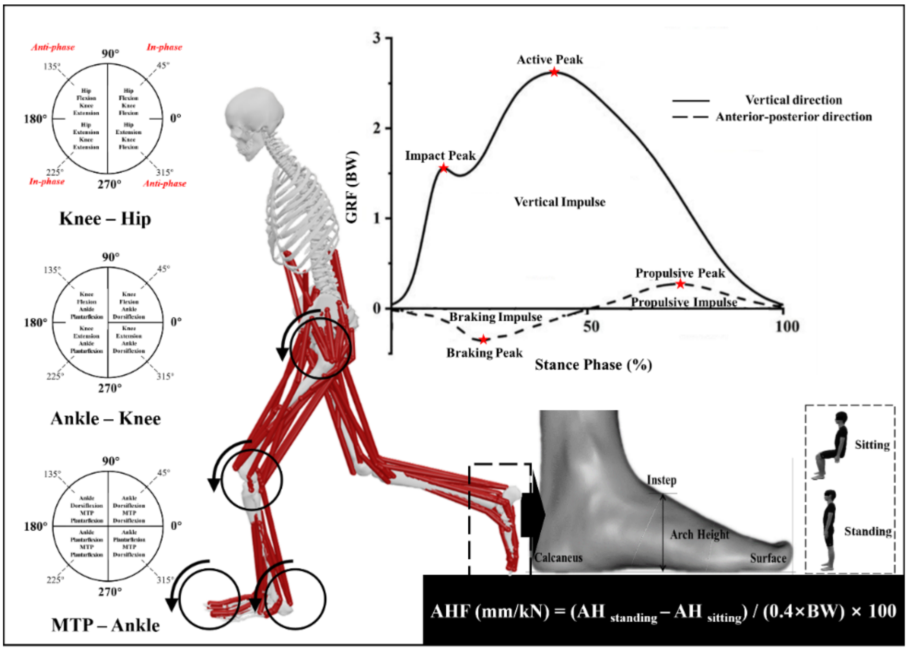

Figure 2 The proposed experimental protocol regarding arch stiffness, lower limb joint coupling coordination, and ground reaction impulse

[8.1 Scientific Publications related to the Thesis Points, P3]

3rd Thesis point: I reconstructed a subject-specific FE model of the foot-ankle complex using the actual three-dimensional geometry of foot bones and soft tissues (Figure 3). A sensitivity study was conducted to evaluate the effects of varying elastic modulus (0-700 MPa) of the PF on the metatarsal stress distribution and force transmission.

- My FE simulations yielded predictions that the peak metatarsal stress gradually reduced with decreasing stiffness until the PF was released, resulting in a reduction of 22.39% compared to the reference value of 350 MPa (Figure 3).
- As PF stiffness gradually decreased to the released situation, there was a corresponding gradual reduction of up to 36% and 72% in contact forces through the TMT and MTP joints.
- Although focal forces related to metatarsalgia could be relieved by adjusting PF stiffness, fatigue damage to the metatarsals may be accelerated since the dorsal aspects of the medial metatarsals are normally loaded in compression, and the bending loads on these bones would be elevated after fascial release.

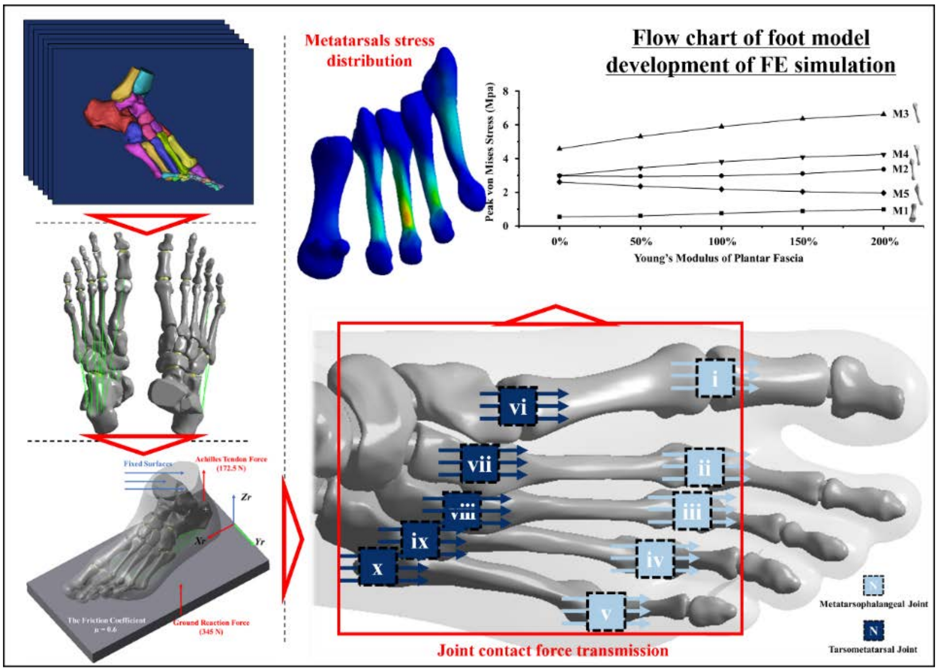

Figure 3 Flow chart of foot model development of FE simulation

[8.1 Scientific Publications related to the Thesis Points, P4 & P5]

6 Possibility to utilize the Results

In this dissertation, a comprehensive method combining biomechanical functional analysis and FE analysis of the foot-ankle complex was applied to reveal foot-specific functional coupling mechanisms related to AS during motion. An understanding of the morphological arch biomechanical function may provide additional insights into foot injury prediction and the comprehensive compensatory adjustment of lower-limb joints during motion. The findings of this study can provide comprehensive biomechanical details and alternative approaches for clinicians and researchers to evaluate and optimize arch orthotics development and reduce stiffness-related arch injury risk.

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8 Publications

8.1 Scientific Publications related to the Thesis Points

1. **Cen, X.**, Yu, P., Song, Y., Sárosi, J., Mao, Z., Bíró, I., & Gu, Y. (2022). The effect of arch stiffness on the foot-ankle temporal kinematics during gait termination: a statistical nonparametric mapping study. Bioengineering, 9(11), 703.
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8.2 Additional Scientific Publications

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