**STUDY PROTOCOL**

**Official Title:**

Morton Toe is Associated With Faster Contractile Properties and Superior Reactive Strength in Female Football Players

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This document contains the complete study protocol including objectives, design, methods, Scientific background, and statistical considerations.

## 1. SCIENTIFIC BACKGROUND

Congenital morphological features are evaluated not only as anatomical variations but also as structural characteristics associated with neuromuscular organization and physical performance. Considering that athletic performance is shaped by the individual's structural characteristics alongside training load and technical skills, the examination of the potential significance of certain morphological phenotypes for performance appears meaningful. In this context, one of the notable morphological variations is Morton toe, a congenital foot morphology characterized by a longer second toe relative to the first (Decherchi, 2005).

From an etiological perspective, it has been proposed that this morphological variation may serve as an indirect marker of prenatal androgen exposure during fetal development (Harrison, 2010; Hönekopp & Watson, 2010; Saino et al., 2006). In addition, experimental animal models have reported an increasing tendency in type II muscle fiber proportion under conditions of prenatal hyperandrogenization (Abbott et al., 2012; Huber et al., 2017; DeChick et al., 2020). These muscle fibers are associated with neuromuscular performance components requiring high speed and power. When these findings are considered collectively, it can be theoretically proposed that individuals with the Morton toe phenotype may exhibit differentiated neuromuscular characteristics. However, the direct and experimental evaluation of this relationship in humans appears challenging due to ethical and methodological constraints. Therefore, indirect approaches through morphological phenotypes offer a meaningful research framework for examining the possible reflections of these biological mechanisms on human performance.

In the existing literature, Morton toe has predominantly been addressed as a clinical and orthopedic variation, associated with metatarsal stress fractures, balance performance, and musculoskeletal problems (Chuckpaiwong et al., 2007; Davidson et al., 2007; Agopyan et al., 2011; Kim, 2024). In contrast, a limited number of studies conducted in athletic populations suggest that second toe length may be associated with certain performance indicators (Kulthanan et al., 2004; Tanaka et al., 2017; Tomita et al., 2018). However, these studies have largely focused on isolated morphological measurements, and the relationship between Morton toe and neuromuscular properties and performance outcomes has not been addressed in the literature with an integrative approach.

In light of previous reports, whether Morton toe constitutes an anatomical variation that creates a disadvantage for athletic performance or a phenotype associated with neuromuscular performance is not clear in the literature. In this context, the present study aimed to examine the potential differences in neuromuscular properties and kinetic performance parameters between female football players with Morton toe and those with normal foot morphology.

## 2. STUDY OBJECTIVES AND HYPOTHESES

### 2.1. Primary Objective

To compare neuromuscular contractile properties (tensiomyographic contraction time, Tc) and kinetic performance (reactive strength index, RSI) between female football players with Morton toe morphology and those with normal foot morphology.

### 2.2. Secondary Objective

To compare additional tensiomyographic parameters (Tr, Td, Ts, Dm) and kinetic performance variables (jump height, peak power/BM, landing net peak force/BM) between groups.

### 2.3. Hypotheses

Primary hypothesis: Female football players with Morton toe morphology would exhibit faster neuromuscular contractile properties and higher reactive strength compared to those with normal foot morphology.

Secondary hypothesis: Morton toe morphology would be associated with higher jump height and peak power values compared to normal foot morphology.

## 3. STUDY DESIGN

This study was designed as a cross-sectional, observational, group comparison investigation. Following assessment of foot morphology, participants meeting the inclusion criteria were classified into two groups: Morton foot group (MG) and normal foot group (NG). All participants underwent neuromuscular and kinetic measurements in a single testing session.

As all participants were active football players, measurements were conducted during the off-season (transition period) within the annual training periodization to minimize confounding effects of intensive training loads. To reduce potential variability related to circadian rhythm, all measurements were performed within the same time-of-day window (±1 hour) for each participant. Participants were instructed to avoid intense physical activity for 24 hours, heavy meals for 3 hours, caffeine for 12 hours, and alcohol for 24 hours prior to testing.

The standardized testing sequence for all participants was: foot morphology assessment, tensiomyography (TMG) measurement, standard warm-up protocol, followed by drop jump test. Standard rest intervals were provided between test stages to prevent acute fatigue from affecting measurement results. All tests were performed in the same laboratory environment, by the same researcher, using the same equipment and standardized procedures.

To minimize measurement and analysis bias, blinding procedures were implemented. Participants were not informed about the specific research topic, and group information was not disclosed. The researcher performing TMG and drop jump measurements was blinded to participants' group classification (single-blind). Statistical analysis was performed by an independent researcher using a coded dataset.

## 4. PARTICIPANTS

### 4.1. Study Population

A total of 47 female football players (age: 20.72 ± 2.76 years) who held a valid sports license for the relevant season and were actively participating in competitive matches volunteered to participate. Prior to the study, participants were provided with detailed information regarding the research protocol and written informed consent was obtained.

### 4.2. Inclusion Criteria

(a) Active female football players with a valid sports license; (b) regular participation in training and competitive matches; (c) bilateral Morton toe morphology ($\Delta \leq -0.30$ mm on both feet) or bilateral normal foot morphology ($\Delta > +0.30$ mm on both feet); (d) body mass index between 18.5 and 29.9 kg/m²; (e) bilateral arch index between 14% and 29%.

### 4.3. Exclusion Criteria

(a) Serious lower-extremity musculoskeletal injury within the past 12 months; (b) neurological or orthopedic disease affecting measurement procedures; (c) current pharmacological use affecting performance; (d) acute pain, injury, or illness on measurement day; (e) menstruation on measurement day (self-reported); (f) inconsistent bilateral foot morphology classification between feet.

### 4.4. Group Classification

Participants were classified into two groups based on bilateral foot morphology assessed using the palpation-based metatarsal length measurement technique described by Davidson et al. (2007) and validated by Martínez-Cepa et al. (2014). Based on the reported minimal detectable change (MDC = 0.30 mm), participants with bilateral metatarsal differences ≤ −0.30 mm were classified as Morton foot group (n = 24), while those with bilateral differences > +0.30 mm were classified as normal foot group (n = 23). Values between −0.30 and +0.30 mm were classified as indeterminate and excluded.

### 4.5. Sample Size Calculation

Sample size was calculated based on the effect size reported by Tanaka et al. (2017), who examined the relationship between forefoot bone lengths and performance in male sprinters. The effect size for second metatarsal bone length differences between fast and slow sprinters (Cohen's d = 1.04) was used as a reference. With a significance level of $\alpha = 0.05$, statistical power of 0.95, and effect size of 1.04, a minimum of 21 participants per group was required. The final sample of 24 and 23 participants per group exceeded this requirement.

### 4.6. Screening and Enrollment

Initially, 97 female football players were assessed for eligibility. Of these, 10 were excluded for BMI criteria, 14 for medial longitudinal arch criteria, and 26 for inconsistent bilateral foot morphology. The remaining 47 participants were classified into Morton foot group (n = 24) and normal foot group (n = 23).

## 5. METHODS

## 5.1. Assessment of Demographic and Physical Characteristics

A personal information form was used to obtain demographic data. Body height and mass were measured using standard procedures.

## 5.2. Determination of Dominant Leg

Dominant leg was determined by asking participants which leg they would use to kick a ball for maximum distance. This method has been shown to achieve 100% agreement between self-reported preference and observed performance in bilateral mobilization tasks (van Melick et al., 2017).

## 5.3. Assessment of Medial Longitudinal Arch Structure

Medial longitudinal arch level was assessed using baropodometry (BTS, S.p.A., Italy). The device recorded plantar pressure distribution in static position and calculated the arch index from plantar pressure data. According to device procedures, bilateral arch index below 14% was classified as high arch and above 28% as low arch (Woźniacka et al., 2019).

## 5.4. Morton Toe Classification

Morton toe was assessed using the palpation-based measurement technique described by Davidson et al. (2007) and validated by Martínez-Cepa et al. (2014). The foot was placed on marked graph paper; the navicular tubercle and the first and second metatarsophalangeal joint creases were identified by palpation and marked. A perpendicular reference line was drawn from the midpoint of the second toenail to the ground; the heel center was determined using a reference line drawn 5 cm proximal to the posterior surface of the calcaneus, and the heel and second toe were aligned on the same axis. A parallel reference line was drawn 2 cm anterior to the foot, and the distances from this line to the first and second metatarsophalangeal joint creases were measured using digital calipers. The difference between metatarsal protrusion distances was calculated and recorded in millimeters.

The reported test-retest reliability of this method (ICC = 0.86; 95% CI: 0.80-0.90), standard error of measurement (SEM = 0.10 mm), and minimal detectable change (MDC = 0.30 mm) were considered. Values between −0.30 mm and +0.30 mm were classified as indeterminate (square foot) and excluded. Bilateral differences ≤ −0.30 mm were classified as Morton toe, and differences > +0.30 mm as normal foot morphology.

## 5.5. Assessment of Neuromuscular Properties (TMG)

Neuromuscular contractile properties were assessed using tensiomyography on the vastus lateralis muscle of the dominant leg. Vastus lateralis was selected as the reference muscle due to its superficial location and high measurement repeatability for assessing muscle architecture and mechanical properties (Lanferdini et al., 2025; Šimunič et al., 2011).

The participant was positioned supine with the trunk supported at 130° and the knee at approximately 130° flexion with a triangular support cushion placed under the knee. The muscle was palpated and the measurement probe (perpendicular to tissue at 90°) and surface electrodes (4 cm apart) were positioned at reference points. Electrical stimulation was initiated at 10 milliamperes (mA) and progressively increased in 10 mA increments until maximal radial displacement (Dm) was obtained. Five-second rest intervals were provided between successive stimulations. All measurements were performed according to device manufacturer-recommended protocols and SENIAM procedures (Hermens et al., 1999; Loturco et al., 2016; Macgregor et al., 2018).

TMG parameters were defined as follows: Tc (Contraction Time): time from 10% to 90% Dm; Tr (Relaxation Time): time from 90% to 50% Dm; Td (Delay Time): time from stimulus onset to 10% Dm; Ts (Sustained Time): duration above 50% Dm; Dm (Displacement): maximal radial deformation.

### 5.6. Assessment of Kinetic Performance (Drop Jump)

Kinetic performance was assessed using a 40-cm drop jump test performed on dual force plates (ForceDecks FD Mini, VALD Performance, Australia). The concurrent validity and test-retest reliability of the ForceDecks system has been demonstrated (González-García et al., 2024; Collings et al., 2024). A standardized familiarization protocol of 5-6 practice jumps progressing from 20 to 40 cm was completed, followed by 5 minutes of rest. Each participant performed 3 maximal drop jumps, and the trial with the highest RSI was selected for analysis.

Drop jump parameters were defined as follows: RSI (Reactive Strength Index): jump height divided by ground contact time (m/s); JH (Jump Height): vertical displacement calculated from flight time (cm); PPI (Peak Power Index): peak power normalized to body mass (W/kg); LPF (Landing Net Peak Force): peak ground reaction force at landing normalized to body mass (N/kg).

### 5.7. Warm-Up Protocol

Prior to performance measurements, participants completed a 15-minute active warm-up consisting of 5 minutes of jogging, 5 minutes of short rapid step-ups, and 5 minutes of stretching exercises.

### 5.8. Outcome Variables

Primary outcomes were determined a priori as contraction time (Tc) and reactive strength index (RSI). Secondary outcomes included relaxation time (Tr), delay time (Td), sustain time (Ts), maximal displacement (Dm), jump height (JH), peak power normalized to body mass (PPI), and landing net peak force normalized to body mass (LPF).

## 6. STATISTICAL CONSIDERATIONS

Statistical analyses were performed using SPSS software (Version 27.0, IBM Corp., Armonk, NY, USA). Continuous variables were presented as mean ± standard deviation for normally distributed data and median [interquartile range] for non-normally distributed data. Normality was assessed using the Shapiro-Wilk test. The significance level was set at $\alpha = 0.05$.

Between-group comparisons were performed using independent samples t-test for normally distributed variables and Mann-Whitney U test for non-normally distributed variables.

Primary outcome variables (Tc and RSI) were designated a priori and were not subjected to multiple comparisons correction. For secondary outcome variables (Tr, Td, Ts, Dm, JH, PPI, LPF), the Holm-Bonferroni sequential correction was applied to control the family-wise error rate. Both uncorrected and corrected p values were reported.

Effect sizes were calculated as Hedges' g with 95% confidence intervals for parametric comparisons and r ($Z/\sqrt{N}$) for nonparametric comparisons. Mean differences with 95% confidence intervals were reported for parametric comparisons only.

Supportive multiple linear regression models were constructed separately for each primary outcome (Tc and RSI). The dependent variable was the respective performance parameter, and independent variables were group (Morton = 1, normal = 0), age, body mass index, and mean bilateral arch index (Mean AI). Left and right arch indices were combined into a single mean variable to reduce multicollinearity. Regression diagnostics included residual normality assessed by Shapiro-Wilk test and multicollinearity assessed by variance inflation factor (VIF). These analyses were used as supportive evidence for the independence of group effects from potential confounders.

Figures and data visualizations were prepared using GraphPad Prism (version 10.4.1).

## 7. ETHICAL CONSIDERATIONS

The research protocol was approved by Giresun University Social Sciences, Natural Sciences and Engineering Research Ethics Committee (Date: 05/11/2025, Decision No: 10/492). The study was conducted in accordance with the Declaration of Helsinki. Prior to the study, participants were provided with detailed information regarding the research protocol and written informed consent was obtained from all participants.

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