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Cross-Limb Associations and Inter-Limb Asymmetry in Segmental Muscle Mass of Elite Athletes

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Abstract

Muscular asymmetries and body composition are key factors influencing performance and injury risk in high-level athletes, particularly in sports requiring unilateral and explosive movements such as handball. The present study aimed to investigate inter-limb muscular asymmetries and the relationships between segmental muscle mass in elite handball players. Eighteen male athletes (aged 17–25 years) were assessed for segmental muscle mass of the upper and lower limbs using bioelectrical impedance analysis. Results indicated no statistically significant differences between the upper limbs, whereas a significant difference was observed between the lower limbs, suggesting the presence of asymmetry at the lower extremities in this cohort. Regression analyses revealed strong positive associations between lower and upper limb muscle mass. In conclusion, segmental muscle mass in one limb may serve as a valid proxy for overall muscularity and should be considered when evaluating asymmetry profiles or designing individualized strength programs in elite handball athletes.

1. Introduction

Handball is a high-performance discipline defined by rapid transitions between attack and defence, substantial physical contact, and the requirement to outscore the opposing team. Athletes must possess the physical capacity to sustain high-intensity efforts and repeatedly execute actions that outmatch their opponents across the entire duration of play. Match performance involves a combination of general locomotor activities—such as walking, running, leaping, and rapid directional changes—and sport-specific skills including passing, receiving, shooting, and defensive blocking. Moreover, elite-level handball differentiates players by position (backs, pivots, wings, and goalkeepers), each with distinct tactical roles, movement profiles, and physiological demands (Michalsik, 2018).

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Handball is a team-based discipline marked by intermittent, high-intensity, and predominantly unilateral movements that impose substantial physiological demands on athletes. As a collision sport, it requires repeated execution of dynamic actions such as sprinting, vertical propulsion, forceful ball release, multidirectional displacement, rotational movements, and rapid variations in velocity and trajectory (García-Sánchez, C., Navarro, R. M., Karcher, C., & De La Rubia, A., 2023), (Cavedon, Zancanaro, & Milanese, 2018). Bioelectrical impedance analysis (BIA) is a non-invasive method used to evaluate the body's fluid status and composition (Lukaski & Moore, 2012). BIA is fast, non-invasive, portable and relatively inexpensive, making it suitable for periodic monitoring of athletes (pre-season, mid-season, post-competition) (Rossi, 2021). In addition to classical compartment estimates (FM, FFM), BIA provides robust information on relative hydration, cell mass and cellular integrity, being less dependent on predictive equations and therefore useful for longitudinal follow-up in athletes (Regli et al., 2021). Inter-limb asymmetry ("IA") refers to differences between limbs (right vs. left) at a morphological (muscle mass, bone) or functional (strength, jump, balance) level (Ojeda-Aravena et al., 2023). Such differences can significantly influence sport-related capabilities, with numerous investigations demonstrating links between interlimb asymmetry (IA) and various performance measures (McGrath et al., 2016), (Ličen, U., Kozinc, Ž. & Marušič, A., 2023), (Fox, K. T., Pearson, L. T. & Hicks, K. M., 2023).

2. Material and methods

A total of 18 elite handball athletes, aged 17 to 25 years, volunteered to participate in this study. All participants were engaged in high-performance training and free of musculoskeletal injuries at the time of testing. Anthropometric characteristics and body composition were assessed using a standardized bioelectrical impedance analysis (BIA) protocol. Segmental muscle mass was extracted for the upper limbs (right and left arm), lower limbs (right and left leg), and trunk. Prior to inferential analysis, the normality of data distribution was evaluated using the Shapiro–Wilk test. To examine bilateral muscular differences, paired-samples t-tests were conducted to compare right vs. left arm muscle mass and right vs. left leg muscle mass. These analyses aimed to identify potential intra-limb asymmetries in upper and lower body segments. To explore the determinants of whole-body muscularity, a multiple linear regression model was performed with total muscle mass as the dependent variable and height and body fat percentage as independent predictors. To investigate contralateral relationships between body segments, several regression and correlation analyses were conducted. A series of linear regression analyses were conducted to examine the cross-limb and ipsilateral relationships in segmental muscle mass. Simple linear regressions were performed using each upper-limb segment (right arm, left arm) as the dependent variable, while corresponding contralateral or ipsilateral lower-limb segments (right leg, left leg) were included as independent predictors. Pearson correlation coefficients were computed to assess the strength and direction of cross-limb associations between right arm and left leg, left arm and right leg, as well as ipsilateral associations between right arm and right leg, and left arm and left leg. In addition, multiple linear regression models were conducted with right- or left-arm muscle mass as dependent variables, including both contralateral leg mass and trunk muscle mass as independent predictors, in order to examine the combined contribution of contralateral and central segments to upper-limb muscularity. All analyses were performed using SPSS (version 26), with statistical significance set at $p < .05$. Assumptions of linearity, homoscedasticity, normality, and absence of multicollinearity were checked prior to interpretation. For all tests, the significance level was set at $p < 0.05$. Descriptive statistics are presented as mean ± standard deviation.

3. Results and Discussions

A multiple regression was performed with total muscle mass as the dependent variable and height and body fat percentage as predictors. The model as a whole explained approximately 25% of the variability in muscle mass ($R^2 = .25$), but the overall F test was not significant, $F(2,15) = 2.51$, $p = .115$ (adjusted $R^2 = .15$). However, analysis of the coefficients shows that, when the other variables are controlled, height had a significant positive effect on muscle mass (B = 0.689 kg per unit height, SE = 0.308, $\beta = .505$, $t = 2.24$, $p = .041$, 95% CI [0.032, 1.347]). Percent body fat did not significantly contribute to the model (B = 0.077, SE = 0.426, $\beta = .041$, $t = 0.18$, $p = .858$, 95% CI [−0.830, 0.985]). These results suggest that, in this sample, height has a stronger influence on muscle mass than percent body fat. The positive effect of height suggests that taller individuals tend to naturally have higher total muscle mass, likely due to longer body segments and increased overall muscle volume. Percent body fat does not have a significant effect, indicating that adiposity is not a relevant predictor of total muscle mass in this sample.

Table 1. *Descriptive statistics for segmental muscle mass in upper and lower limbs*

	Mean	Std. Deviation	Std. Error	Variance
Muscle Mass Left Arm	4.29	0.62	0.42	0.38
Muscle Mass Left Leg	12.08	1.17	0.28	1.37
Muscle Mass Right Arm	4.36	0.59	0.14	0.35
Muscle mass Right Leg	12.23	1.22	0.29	1.49

The results of the paired-samples t-test indicated that there was no statistically significant difference between the muscle mass of the left arm (M = 4.29 kg, SD = 0.62) and that of the right arm (M = 4.36 kg, SD = 0.59), t(17) = -

1.56, p = .138, 95% CI [-0.157, 0.024] (figure 1). Although the muscle mass of the right arm is slightly higher on average, the difference is not statistically significant. This result suggests a muscular symmetry between the left and right arms in the handball players analyzed, possibly due to the involvement of both upper limbs in playing and training activities.

For the lower limbs, the t-test showed a statistically significant difference between the muscle mass of the left leg (M = 12.08 kg, SD = 1.17) and that of the right leg (M = 12.23 kg, SD = 1.22), t(17) = -2.50, p = .023, 95% CI [-0.267, -0.022]. The right leg has a significantly higher muscle mass than the left leg. This asymmetry may reflect a functional dominance of the right lower limb, frequently found in right-handed athletes, possibly related to the main impulse used in changes of direction. Overall, the results suggest symmetry between the arms, but a significant asymmetry between the lower limbs, with a slight predominance of muscle mass on the right side. This distribution could represent a specific adaptation to technical gestures in handball, where the jumping impulse and stabilization are frequently performed with the dominant lower limb, while the opposite arm is involved in the throw.

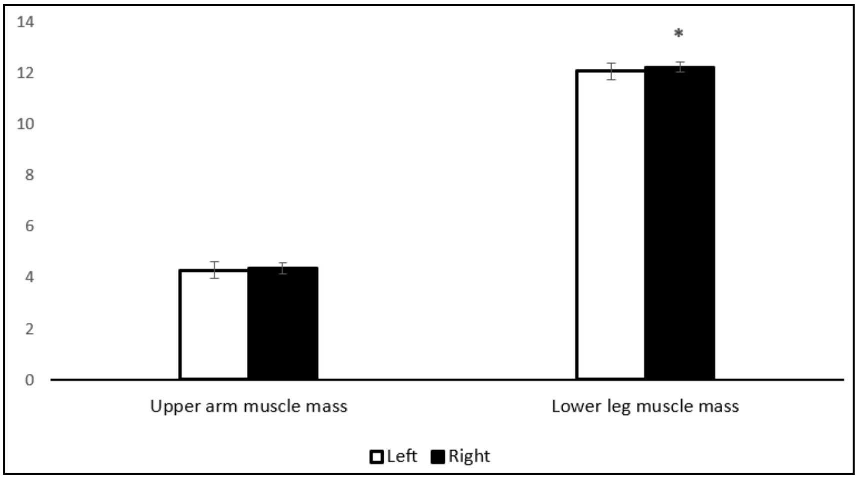

Figure 1. *Muscle mass (kg) in the upper and lower limbs; results are presented as mean ± SD with 95% confidence interval; Symbol (*) indicates significant difference p ≤ .05 within-group.*

Segmental correlations showed a marked contralateral association: left-arm muscle mass was strongly correlated with left-leg muscle mass (r = .849, p < .001, 95% CI [.599,.947]. Similarly, right-arm muscle mass was strongly correlated with left-leg muscle mass (r = 0.849, p < 0.001, 95% CI [.587, .941]. These results are consistent with the handball thrower motor model (one-leg hop with opposite-limb throw). To examine the contralateral relationship between body segments, a simple linear regression was performed in which right-arm muscle mass was entered as the dependent variable and left-leg muscle mass as the independent predictor (figure 2).

The analysis indicated that the regression model is statistically significant,

$F(1,16) = 71.30$, $p < .001$, and explains 81.7% of the variance in right arm muscle mass ($R^2 = .817$, adjusted $R^2 = .805$). The high value of R^2 shows a very high explanatory power of the model, suggesting a close relationship between left leg and right arm muscle mass. The model shows that the left leg and right arm develop “in tandem”, and their development patterns are so closely linked that one can almost completely predict the other. This high proportion of explained variance suggests that muscle distribution across limbs follows a coherent pattern in trained handball athletes, likely reflecting shared neuromuscular demands, coordinated bilateral loading, and systemic adaptations. Overall, the significant model indicates that segmental muscle mass is not independent across limbs but exhibits meaningful inter-limb relationships that should be considered when evaluating asymmetry and body composition in athletic populations. The regression coefficient for muscle mass of the left leg is significantly positive, $B = 0.459$, $SE = 0.054$, $\beta = 0.904$, $t(16) = 8.44$, $p < .001$, 95% CI [0.344, 0.574]. This means that for every 1 kg increase in left leg muscle mass, right arm mass increases, on average, by 0.459 kg.

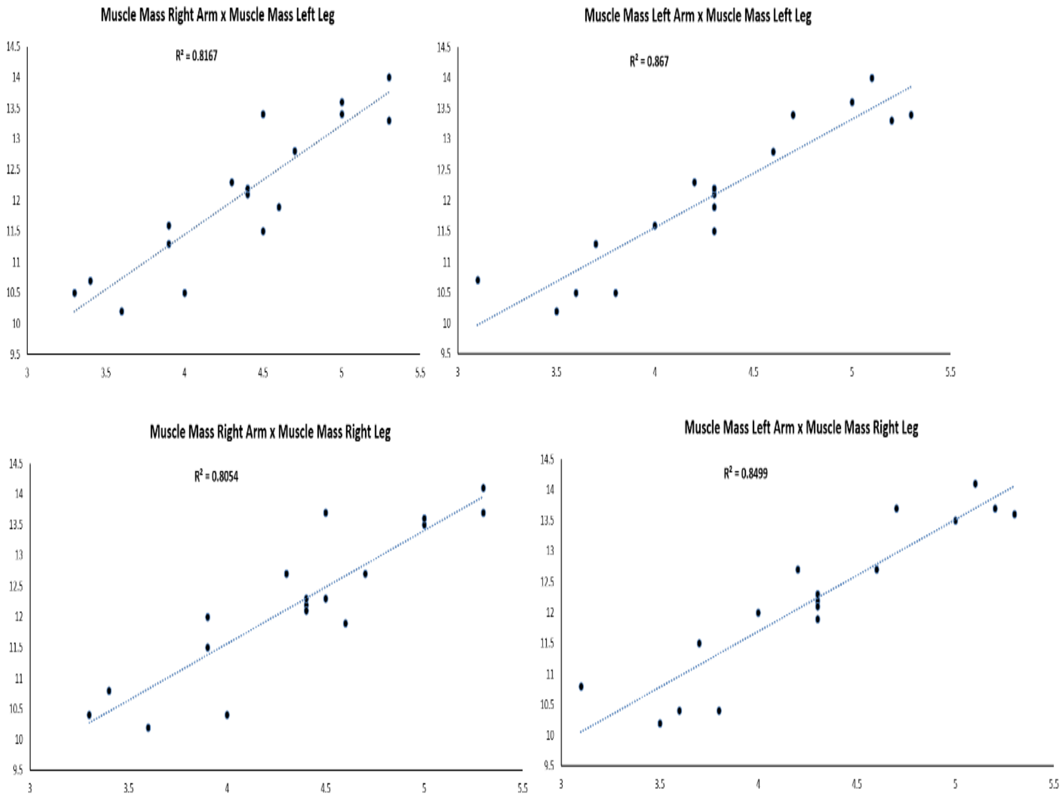

Figure 2. *The relationship between the muscle mass of the right arm and the muscle mass of the left leg, evidenced by linear regression ($R^2 = 0.8167$), muscle mass left arm and muscle mass left leg ($R^2 = 0.867$), muscle mass right arm and muscle mass right leg ($R^2 = 0.8054$), muscle mass left arm and muscle mass right leg ($R^2 = 0.8499$)*

The linear regression analysis examined whether right-leg muscle mass predicts left-arm muscle mass. The overall model was statistically significant, $F(1,16) = 90.59$, $p < .001$, indicating that the predictor reliably explains variance in the dependent variable. The model accounted for a very large proportion of variance in left-arm muscle mass, $R = .922$, $R^2 = .850$, with an adjusted $R^2 = .841$, $SE = .246$, meaning that approximately 84–85% of the variation in left-arm muscle mass is explained by right-leg muscle mass. Regarding the regression coefficients, the unstandardized slope for right-leg muscle mass was $B = 0.466$, with a standard error of $SE = 0.049$, indicating a precise estimate. The standardized coefficient was large and positive, $\beta = 0.922$, showing a strong effect size. The predictor was statistically significant, $t(16) = 9.52$, $p < .001$, and the 95% confidence interval for the slope was [.362, .570], confirming that the relationship is both robust and meaningfully positive. The main predictor, right leg muscle mass, had a strong positive effect on left arm muscle mass $B = 0.466$, $SE = 0.049$, $\beta = 0.922$, $t(16) = 9.52$, $p < .001$, 95% CI [0.362, 0.570]. This means that for every 1 kg increase in right leg muscle mass, left arm muscle mass increases by an average of 0.466 kg. The narrow confidence interval (.362–.570) confirms the stability and precision of the estimate. The standardized coefficient value $\beta = 0.922$ shows a very strong effect, suggesting that right leg muscle mass is a robust predictor of left arm muscle mass in this sample of athletes. The findings of the present study offer clear evidence that muscular development across limbs is strongly interconnected in high-performance handball athletes. The strong positive association observed between the muscle mass of the right leg and that of the left arm (e.g., $B = 0.466$, $SE = 0.049$, $\beta = 0.922$, $t(16) = 9.52$, $p < .001$, 95% CI [0.362, 0.570]) suggests that increases in segmental muscle mass are not isolated phenomena but instead reflect a coordinated and systemic pattern of musculoskeletal development. Practically, this means that for every 1 kg increase in right-leg muscle mass, left-arm muscle mass increases by approximately 0.466 kg, highlighting a strong cross-limb relationship.

Such results likely emerge from global training adaptations typical of elite handball preparation, where whole-body strength, repeated high-intensity actions, and multi-planar movements impose integrated neuromuscular demands. This systemic load distribution promotes parallel muscular development even in anatomically distant segments. Consequently, muscularity in one limb may serve as a meaningful proxy for an athlete's overall muscularity and should be considered when evaluating asymmetry profiles.

Moreover, the strength of the regression model ($R = .922$, $R^2 = .850$, adjusted $R^2 = .841$, $F(1,16) = 90.59$, $p < .001$) demonstrates that right-leg muscle mass accounts for approximately 85% of the variance in left-arm muscle mass. This degree of shared variance reinforces the notion that limb development in high-level athletes follows coherent, body-wide patterns rather than independent, localized hypertrophy.

Overall, these results underscore that muscular symmetry or asymmetry cannot be interpreted solely through unilateral measurements; instead, they are embedded within broader systemic characteristics of body composition and training. Practitioners should use this information to better understand athlete profiles, monitor development, and design individualized strength programs that acknowledge these inter-limb relationships.

Discussions

Studies indicates that inter-limb asymmetry may hinder results, especially during demanding actions that rely on coordinated effort from both legs, such as change-of-direction speed (CODS). CODS refers to rapidly altering movement velocity or trajectory according to a set motor pattern (Nimphius, S., Callaghan, S. J., Bezodis, N. E. & Lockie, R. G., 2018). Another study conducted by (Lijewski, M., Burdukiewicz, A., Pietraszewska, J., Andrzejewska, J. & Stachoń, A., 2021) investigated 36 professional handball players, using segmental bioimpedance (SBIA), to measure muscle mass and fat on the right and left sides (limbs, trunk). They reported discrepancies between right and left in most of the analyzed parameters: muscle, fat, and also observed “cross-asymmetry” and significant bilateral differences in the trunk. This type of morphological (structural) asymmetry can influence function and strength, but also the risk of injury, depending on how much it deviates from an “adaptive asymmetry”. Segmental body composition (e.g., muscle mass on one limb versus another) may help explain differences in performance on motor tests (jumps, sprints, changes of direction) (Stachoń, A., Pietraszewska, J., & Burdukiewicz, A., 2025). In the case of handball, a study on players highlighted that body posture and composition (mass base, muscle-fat ratio) influence postural stability and the ability to generate force and power in game-specific actions (Wilczyński, J., Cieślik, M., Maszczyk, A. & Zwierzchowska, A., 2022). Moreover, it is not only morphological parameters that matter: a recent study showed correlations between body composition (fat-free mass, total body water) and psychomotor skills (reaction time, movement) in handball players (Śliż et al., 2024). The work of Chapelle, Bishop, Clarys and D’Hondt (2021) examined uneven body-composition profiles in competitive tennis athletes. Their sample consisted of 22 players (22 ± 3.6 years), and the analysis centered on whether discrepancies in fat-free mass (FFM) were linked to differences in one-sided performance tests. Despite detecting clear upper- and lower-limb FFM imbalances—on both the preferred and non-preferred sides—the researchers reported no meaningful associations between these structural discrepancies and outcomes such as handgrip force, single-leg change-of-direction time, or unilateral jump performance (Chapelle L. et. al., 2021). A more recent study has shown that a certain degree of muscle asymmetry (5–10%) between the legs, favoring the jumping leg, may actually have a protective role against injury in handball players. However, an imbalance greater than what is considered "typical for the sport" may increase the risk of injury and impair performance (Zsakai et al., 2024). Studies on handball players and team athletes show specific segmental adaptations: increased muscle mass in segments frequently involved in dominant actions (arms for throwing, legs for momentum), with frequent occurrence of functional asymmetries. These segmental changes are consistent with the literature reporting specific adaptations to the type of training and with results linking asymmetry to performance and injury risk (Lijewski et al., 2021; Carrasco-Fernández, et al., 2023; Stachoń et al., 2025). There is direct evidence and functional hypotheses supporting contralateral connections (right arm ↔ left leg and vice versa) in sports involving jumping and throwing on one leg, and some studies in handball players and other sports populations indicate strong associations between contralateral segmental masses and performance on jump or change of direction tests. However, many papers recommend verifying these associations by controlling for general body size (height, FFM), as strong correlations may simply reflect "athleticism"/general size (Yamada et al., 2013), (Madruga-Parera et al., 2020), (Cadens Roca, et al., 2023). Meta-analyses and observational studies suggest that lower limb muscle mass is a consistent predictor of momentum and speed capacity (sprint, vertical jump), and upper limb and trunk muscle mass correlates with throwing velocity and productivity in throwing sports. Thus, the contralateral correlations you observe (e.g., left arm ↔ right leg) may have real functional significance (Yamada et al., 2013). Recent literature summarizes practical thresholds (e.g., asymmetry > 10% considered high/clinically relevant in many contexts), but recommends context-dependent interpretation (gender, competitive level, role on the field). In addition, meta-analyses on the effects of asymmetry on performance indicate moderate relationships between asymmetry and decreased performance in certain tests (sprint), but the evidence is heterogeneous (Madruga-Parera et al., 2020), (Domaradzki, 2024). The results obtained by Ojeda-Aravena et al. (2023) showed that imbalances in body composition (BC), fat-free mass (FFM), and lean soft tissue mass (LSTM) were inversely associated with most outcomes of the FSKTMULT test. Similar tendencies were reported by Bell, Sanfilippo, Binkley, & Heiderscheit (2014) who explored how BC-related differences between limbs relate to bilateral task performance in university athletes. Their sample included 167 participants (20 ± 1.3 years; 103 men, 63 women). They observed that unequal FFM in the legs accounted for roughly one-fifth of the variability in strength asymmetry. They also noted that when power discrepancies surpassed 10%, performance declined. Within that cohort, 95% exhibited strength differences between −11.8% and 16.8%, and power differences between −9.9% and 11.5%, with fewer than 4% showing disparities above 15%. Friesen, Lang, Chad and Oliver (2022) examined the asymmetry–performance relationship from another perspective. Studying softball pitchers, they contrasted athletes with normal versus elevated body-fat levels. Symmetry in isometric strength and mobility was assessed using a handgrip device and an inclinometer. DXA scans were used to detect left–right differences and subtle functional variations between groups. Their results indicate that alterations in BC may impair certain movement tasks.

4. Conclusions

Correlational analyses revealed strong relationships between functionally associated body segments in the game, suggesting a developmental pattern influenced by the specific demands of this sport. The high correlations between the muscle mass of the arm and that of the opposite lower limb reflect possible adaptations related to the biomechanics of throwing and swinging, central elements in handball performance. Overall, the findings of this study highlight the usefulness of BIA analysis not only as a tool for monitoring body composition, but also as a method for interpreting physiological adaptations relevant to handball performance. The identification of clear relationships between body segments allows for a more nuanced understanding of muscle development, providing useful benchmarks for coaches, physical trainers and medical personnel. These data can contribute to the optimization of training programs, the prevention of musculoskeletal imbalances and the individualized orientation of athletes' training.

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