







Inter-limb isometric strength symmetry and its association with whole-body force production in physically active young adults

-  **Emmanuel Nicolás Ignacio Morales**  . University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.
-  **Darío Fernando Cappa**. University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.
-  **Leandro Nodari**. University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.
-  **Marco Ramos**. University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.
-  **Ezequiel Aquistapace**. University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.

ABSTRACT

Background: Inter-limb strength asymmetries are commonly evaluated using dynamic or isokinetic assessments, yet less is known about bilateral force symmetry during whole-body isometric tasks and how it relates to overall neuromuscular strength expression in physically active populations. **Purpose:** To characterize upper- and lower-limb inter-limb isometric strength symmetry and examine the association between handgrip strength and whole-body isometric force production in physically active young adults. **Methods:** Eighty-eight physically active university students (44 males, 44 females) completed maximal handgrip (HG) and bilateral isometric mid-thigh pull (IMTP) tests. From IMTP trials, peak force, average force, impulse, and rate of force development were obtained, while maximal grip strength was recorded for both hands. Inter-limb asymmetry was calculated using the symmetry angle. Sex differences and associations between HG and IMTP variables were analyzed using parametric or non-parametric statistics. **Results:** Males showed significantly greater absolute strength than females across all HG and IMTP variables ($p < .01$). Inter-limb asymmetry values for both upper and lower limbs were small and below commonly reported clinical thresholds. Physical activity level was not associated with asymmetry magnitude. In contrast, handgrip strength demonstrated strong positive correlations with IMTP peak force, average force, and impulse ($\rho > .70$, $p < .001$). **Conclusions:** Physically active young adults exhibit minimal inter-limb isometric asymmetry despite clear limb dominance. The strong relationship between handgrip strength and IMTP-derived force variables suggests that handgrip testing may provide a practical indicator of global isometric strength capacity, although task-specific assessments remain necessary for detailed neuromuscular evaluation.

Keywords: Sport medicine, Muscle strength, Students, Asymmetries, Imbalances, Handgrip, Isometric mid-thigh pull.

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 **Corresponding author.** University Institute of Physical Activity and Sport «Dr. Jorge E. Coll». Mendoza, Argentina.

E-mail: enig_mor_91@hotmail.com

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INTRODUCTION

Inter-limb strength asymmetries are a common feature of human movement and reflect the combined influence of limb dominance, task-specific motor learning and neuromuscular organisation (Bishop et al., 2018; Newton et al., 2006). While a certain degree of bilateral variability is considered physiological, pronounced asymmetries in force production have been associated with impaired movement efficiency and an increased risk of musculoskeletal injury in both athletic and physically active populations (Bishop et al., 2016; Guan et al., 2022; Hietamo et al., 2021). Consequently, the assessment of inter-limb strength symmetry has become a relevant component of performance monitoring and injury risk screening in sport and exercise science.

Historically, the investigation of bilateral strength asymmetries has predominantly relied on isokinetic dynamometry, particularly to quantify agonist–antagonist and limb-to-limb torque imbalances (Knapik et al., 1991; Yoshioka et al., 2011). Although this approach provides valuable joint-specific information, its ecological validity is limited, as isokinetic tasks do not replicate the multi-joint, whole-body force demands encountered in most sporting and daily activities (Jones & Bampouras, 2010). Moreover, the logistical constraints associated with isokinetic testing restrict its widespread use in applied settings, prompting the need for alternative assessment strategies that balance methodological rigour with practical feasibility.

In recent years, isometric assessments have gained prominence as reliable and time-efficient tools for evaluating maximal force-generating capacity. Among these, the bilateral isometric mid-thigh pull (IMTP) has emerged as a robust indicator of whole-body isometric strength, demonstrating strong associations with dynamic performance outcomes such as sprinting, jumping and weightlifting (Comfort et al., 2019; Kawamori et al., 2006). The IMTP is thought to reflect not only peripheral muscular capacity but also central neural drive and intermuscular coordination, making it a suitable task for examining bilateral force-sharing strategies during maximal voluntary efforts (McGuigan et al., 2012; Suchomel et al., 2018).

Despite its widespread application, the majority of IMTP research has focused on peak force and rate of force development as indicators of performance, with comparatively less attention given to inter-limb force symmetry during bilateral pulling tasks (Keogh et al., 2020; McMaster et al., 2014). This represents a notable gap, as bilateral tasks may mask meaningful asymmetries that could influence force distribution, movement efficiency, or long-term injury risk (Bishop et al., 2018). Furthermore, little is known about the extent to which inter-limb asymmetries observed in lower-body isometric tasks are mirrored in upper-limb force production within the same individuals.

Handgrip strength testing is widely recognised as a simple and reliable measure of maximal voluntary force production and has been extensively used as a marker of general health, functional capacity and neuromuscular integrity (Bohannon, 2015, 2019; Hogrel, 2015). Beyond its clinical applications, handgrip strength has been proposed as a proxy for global strength capacity, likely reflecting shared neural determinants such as motor unit recruitment efficiency and voluntary activation (Innes, 1999; Lim et al., 2020). However, the relationship between handgrip strength and whole-body isometric force production, particularly in relation to bilateral symmetry, remains insufficiently explored in physically active but non-elite populations.

Understanding whether upper-limb isometric strength reflects lower-limb whole-body force production may have practical implications for screening and monitoring in environments where comprehensive testing batteries are not feasible (Almashaqbeh et al., 2022; Eckman et al., 2014). Additionally, clarifying the magnitude and relevance of inter-limb asymmetries across different anatomical regions may help

contextualise commonly used clinical thresholds within physically active populations, where injury risk profiles and training exposures differ from those of elite athletes (Bishop et al., 2016).

Therefore, the aims of this study were: (1) to characterise inter-limb isometric strength symmetry in both the upper and lower limbs using handgrip and bilateral IMTP assessments in physically active young adults and (2) to examine the association between handgrip strength and whole-body isometric force production. It was hypothesised that inter-limb asymmetry values would remain low in this population and that handgrip strength would demonstrate a strong positive association with IMTP-derived force variables, reflecting shared neuromuscular determinants of maximal isometric force production.

MATERIALS AND METHODS

Participants

The sample consisted of 88 students (44 male, 44 female) from the Physical Education Teaching programme. Inclusion criteria required students to be active in practical classes but not engaged in systematic competitive sports or federated athletics. Exclusion criteria included any musculoskeletal injury in the six months prior to the study or pain preventing maximal voluntary contraction. All participants provided informed consent in accordance with the Declaration of Helsinki (World Medical Association, 2013). The study protocol was approved by a University Research Committee (Mendoza, Argentina).

Sample size estimation and justification

An a priori sample size estimation was conducted using G*Power software (version 3.1.9.7; Heinrich Heine University, Düsseldorf, Germany). Based on previous literature reporting moderate-to-large associations between handgrip strength and whole-body isometric force production (Rhodes et al., 2022; Comfort et al., 2019; McGuigan et al., 2012), a minimum sample size of 64 participants was required to detect a large correlation ($\rho = .50$) with an alpha level of .05 and a statistical power of 0.80. To account for potential participant attrition and to permit sex-specific analyses, a total of 88 participants were recruited and included in the final analysis.

Procedures

Participants attended a single laboratory session (~30 min). After completing a physical activity questionnaire (Hagströmer et al., 2006), anthropometric profiles were established. Body mass was recorded using a precision scale (Urbe II Full 300; 0.100 kg resolution), standing height using a Harpenden stadiometer and waist circumference using a standard anthropometric tape. Additionally, the waist-to-height ratio was calculated (World Health Organisation (WHO), 2008). Hand and leg dominance were determined by self-reported preference for writing and kicking a ball, respectively (van Melick et al., 2017).

Isometric protocols

A standardised warm-up was performed prior to testing (Comfort et al., 2019). Handgrip (HG) test was measured using a digital dynamometer (Kensbro EH106). Participants performed one submaximal trial followed by two maximal efforts per hand. The highest values were recorded (Almashaqbeh et al., 2022; Eckman et al., 2014; Hogrel, 2015; Innes, 1999; Lim et al., 2020).

Isometric mid-Thigh Pull (IMTP) was performed on dual force plates (PASCO Scientific 2-axis PS-2142, 1000 Hz sampling rate) within a custom anchoring rig. Body position was standardised with hip angles of 140–150° and knee angles of 125–145°. Two submaximal familiarisation trials were followed by three maximal

trials of 3 seconds duration (Comfort et al., 2019; Keogh et al., 2020; McMaster et al., 2014). The order of testing was fixed (HG followed by IMTP) to prevent upper limb fatigue from influencing HG results.

Data analysis

For the IMTP, PF, F_{mean} , RFD and IMP were analysed, together with values normalised to body mass. For the handgrip test, right (HG_R) and left (HG_L) grip strength, as well as the mean value (HG_{mean}), were assessed in both absolute and body mass-normalised terms ($HG_R \cdot \text{kg}^{-1}$, $HG_L \cdot \text{kg}^{-1}$ and $HG_{\text{mean}} \cdot \text{kg}^{-1}$). Inter-limb asymmetry was quantified using the symmetry angle (SA) method (Zifchock et al., 2008), calculated as:

$$SA = \left(\frac{45^\circ - \arctan\left(\frac{x_{\text{left}}}{x_{\text{right}}}\right)}{90^\circ} \right) \times 100$$

Statistical analysis

All statistical analyses were performed using JASP software (version 0.16.1; University of Amsterdam, The Netherlands) and Microsoft Excel. Data distribution was assessed using the Shapiro–Wilk test and visual inspection of histograms and Q–Q plots was conducted to support normality assessment. When assumptions of normality were met, parametric analyses were applied; otherwise, non-parametric alternatives were used.

Descriptive statistics are presented as mean \pm standard deviation (SD). Between-sex differences in anthropometric and strength variables were examined using independent samples t-tests or Mann–Whitney U tests, as appropriate. Effect sizes were calculated to quantify the magnitude of differences, using Cohen's *d* for parametric comparisons and rank-biserial correlation (*r*) for non-parametric tests and interpreted according to established thresholds (small, moderate, large). Effect sizes and correlation magnitudes were interpreted according to established thresholds (Hopkins et al., 2009). Statistical significance was set at $p < .05$.

Absolute reliability was assessed using the coefficient of variation (CV%) calculated across the pooled sample for each original performance variable. As recommended for inter-limb asymmetry analyses, CV values were not calculated separately by sex, as measurement error was considered a property of the test rather than of the participant group (shown in Supplementary Table S1).

Supplementary Table S1. Coefficient of variation.

	CV
HG Right (kgf)	0.310
HG Left (kgf)	0.328
IMTP Peak Force (N)	0.317
IMTP Mean Force (N)	0.321
IMTP RFD (N·s ⁻¹)	0.675
IMTP Impulse (N)	0.326

Note. HG: Handgrip; IMTP: isometric mid-thigh pulls; CV: coefficient of variation. For the IMTP, reliability was assessed using bilateral force–time variables, as the test was performed bilaterally and limb-specific force outputs could not be isolated.

Inter-limb asymmetry was quantified using the symmetry angle method, which accounts for bilateral force contributions without assuming limb dominance. Group differences in asymmetry magnitude were assessed using the same parametric or non-parametric approach described above.

Associations between handgrip strength and IMTP-derived variables were examined using Pearson's product-moment correlation coefficient or Spearman's rank correlation coefficient, depending on data distribution. Correlation magnitudes were interpreted using conventional criteria (trivial < .10, small .10 – .29, moderate .30 – .49, large \geq .50). Where relevant, the coefficient of determination (R^2) was reported to aid interpretation of shared variance.

The level of statistical significance was set at $p < .05$. Exact p-values are reported where possible and confidence intervals (95%) are provided for key estimates to facilitate interpretation beyond null-hypothesis significance testing.

RESULTS

Sample

Significant sex-related differences were observed in body mass ($F = 53.619$, $p < .001$, $\eta^2 = 0.384$, 95% CI: 0.230–0.515), height ($H = 44.131$, $p < .001$, $\eta^2 = 0.502$, 95% CI: 0.344–0.648), body mass index (BMI) ($H = 7.677$, $p = .006$, $\eta^2 = 0.078$, 95% CI: 0.000–0.207), waist circumference ($H = 39.791$, $p < .001$, $\eta^2 = 0.451$, 95% CI: 0.259–0.664) and waist-to-height ratio ($H = 11.041$, $p < .001$, $\eta^2 = 0.117$, 95% CI: 0.018–0.282), as presented in Table 1.

Table 1. Sample (mean \pm SD).

	Female	Male
Age (years)	23.21 \pm 3.76	23.11 \pm 3.21
Body Mass (kg)	60.19 \pm 8.20	75.99 \pm 11.73 ***
Height (cm)	159.81 \pm 7.35	172.97 \pm 6.67 ***
BMI	23.55 \pm 2.65	25.62 \pm 4.05 **
Waist circumference (cm)	71.11 \pm 5.45	82.41 \pm 8.77 ***
Waist-to-height ratio	0.45 \pm 0.04	0.48 \pm 0.06 ***

Note. * $p < .05$; ** $p < .01$; *** $p < .001$.

Table 2. IMTP variables (mean \pm SD).

	Female	Male
IMTP PF (N)	789 \pm 145	1227 \pm 295 ***
IMTP PF kg^{-1} (N kg^{-1})	13.25 \pm 2.45	16.19 \pm 3.16 ***
IMTP F_{mean} (N kg^{-1})	680 \pm 128	1053 \pm 262 ***
IMTP F_{mean} kg^{-1} (N kg^{-1})	11.41 \pm 2.14	13.91 \pm 2.90 ***
IMTP RFD (N s^{-1})	1325 \pm 747	1385 \pm 1.063
IMTP RFD kg^{-1} (N s^{-1} kg^{-1})	22.44 \pm 13.47	18.54 \pm 14.87
IMTP IMP (N kg^{-1})	2031 \pm 381	3220 \pm 790 ***
IMTP IMP kg^{-1} (N kg^{-1})	34.16 \pm 6.91	42.21 \pm 8.51 ***

Note. IMTP: isometric mid-thigh pull; PF: peak force; RFD: rate of force development; IMP: impulse. * $p < .05$; ** $p < .01$; *** $p < .001$.

Isometric mid-Thigh Pull (IMTP)

Left lower limb dominance was reported by 86.36% of participants ($n = 76$). Male participants demonstrated significantly greater absolute values for PF ($F = 77.899$, $p < .001$, $\eta^2 = 0.475$, 95% CI: 0.326–0.592), PF normalized ($F = 23.707$, $p < .001$, $\eta^2 = 0.216$, 95% CI: 0.082–0.359), F_{mean} ($F = 71.943$, $p < .001$, $\eta^2 = 0.455$, 95% CI: 0.304–0.575), F_{mean} normalized ($F = 21.126$, $p < .001$, $\eta^2 = 0.197$, 95% CI: 0.068–0.340), IMP ($F =$

78.439, $p < .001$, $\eta^2 = 0.477$, 95% CI: 0.328–0.593) and IMP normalized ($F = 23.756$, $p < .001$, $\eta^2 = 0.216$, 95% CI: 0.082–0.360) compared with females. No significant sex-related differences were observed for RFD absolute or normalized ($p < .05$) (Table 2).

The reliability of IMTP-derived variables was excellent, with an intraclass correlation coefficient (ICC) of .955 (95% CI: 0.937–0.969).

Handgrip test (HG)

Right-hand dominance was reported by 87.5% of the sample ($n = 77$). Male participants demonstrated significantly higher values for HG_R ($F = 140.031$, $p < .001$, $\eta^2 = 0.620$, 95% CI: 0.495–0.708), HG_L ($F = 137.632$, $p < .001$, $\eta^2 = 0.615$, 95% CI: 0.490–0.705) and HG_{mean} ($F = 153.268$, $p < .001$, $\eta^2 = 0.641$, 95% CI: 0.521–0.725), $HG_L \cdot kg^{-1}$ ($F = 46.226$, $p < .001$, $\eta^2 = 0.350$, 95% CI: 0.196–0.484), $HG_R \cdot kg^{-1}$ ($F = 49.203$, $p < .001$, $\eta^2 = 0.364$, 95% CI: 0.210–0.497) and $HG_{mean} \cdot kg^{-1}$ ($F = 52.560$, $p < .001$, $\eta^2 = 0.379$, 95% CI: 0.225–0.511) compared with females (Table 3).

The reliability of handgrip-derived variables was excellent, with an intraclass correlation coefficient (ICC) of .918 (95% CI: 0.877–0.945).

Table 3. HG variables (mean \pm SD).

	Female	Male
HG_R (kgf)	26.83 \pm 5.05	43.99 \pm 8.19 ***
$HG_R \cdot kg^{-1}$ (kgf kg^{-1})	0.45 \pm 0.09	0.58 \pm 0.09 ***
HG_L (kgf)	25.13 \pm 5.18	42.40 \pm 8.28 ***
$HG_L \cdot kg^{-1}$ (kgf kg^{-1})	0.42 \pm 0.09	0.56 \pm 0.10 ***
HG_{MEAN} (kgf)	25.98 \pm 4.86	43.19 \pm 7.84 ***
$HG_{MEAN} \cdot kg^{-1}$ (kgf kg^{-1})	0.44 \pm 0.09	0.57 \pm 0.09 ***

Note. HG: handgrip; R = right; L = left. * $p < .05$; ** $p < .01$; *** $p < .001$.

Physical Activity (IPAQ questionnaire)

No significant differences were found between sexes regarding physical activity levels ($p > .05$) (Table 4).

Table 4. IPAQ results (mean \pm SD).

Activity		Female	Male
Intense	n	3.19 \pm 1.22	3.43 \pm 1.26
	min	94.87 \pm 32.26	91.25 \pm 33.33
Moderate	n	2.94 \pm 1.41	3.13 \pm 1.74
	min	75.92 \pm 28.19	69.70 \pm 26.75
Low	n	4.61 \pm 2.12	5.21 \pm 1.83
	min	63.00 \pm 76.26	47.84 \pm 33.51
Sedentary	min	168.00 \pm 91.21	180.75 \pm 98.12

Note. n = days per week; min = minutes per day.

Asymmetries

Crucially, no statistically significant differences were observed in asymmetry levels (SA) for either HG or IMTP variables between groups (Table 5). Asymmetry percentages were for HG: $1.70 \pm 4.00\%$ and for IMTP PF $2.33 \pm 4.71\%$.

Table 5. Isometric asymmetries (mean \pm SD).

	Female		Male	
	Mean	Var	Mean	Var
HG asymmetry (%)	2.20 \pm 4.15	17.17	1.21 \pm 3.83	14.64
IMTP PF asymmetry (%)	2.31 \pm 3.67	13.43	2.34 \pm 5.62	31.53
IMTP F _{mean} asymmetry (%)	2.45 \pm 3.59	12.90	2.48 \pm 5.66	32.01
IMTP RFD asymmetry (%)	-1.16 \pm 13.63	185.89	-0.54 \pm 12.90	166.39
IMTP IMP asymmetry (%)	2.31 \pm 3.67	13.43	2.35 \pm 5.62	31.53

Note. HG: Handgrip; IMTP: isometric mid-thigh pull; PF: peak force; F_{mean}: average force; RFD: rate of force development; IMP: impulse; Var: Variance. * $p < .05$; ** $p < .01$; *** $p < .001$.

Correlations

No significant associations were observed between physical activity levels and asymmetry magnitudes ($p > .05$). In contrast, strong positive correlations were identified between handgrip strength and IMTP performance. Specifically, both HGR and HGL were strongly associated with IMTP PF ($r = .708 - .726$, $p < .001$), F_{mean} ($r = .708 - .726$, $p < .001$) and IMP ($r = .697$, $p < .001$), with all confidence intervals indicating large effect sizes.

In addition, body mass was strongly correlated with handgrip strength (HGR: $r = .739$, HGL: $r = .677$; $p < .001$) and IMTP outcomes, including PF ($r = .706$, $p < .001$), F_{mean} ($r = .691$, $p < .001$) and IMP ($r = .702$, $p < .001$). Similarly, stature showed moderate-to-strong positive associations with handgrip strength for both limbs (HGR: $r = .673$; HGL: $r = .696$; $p < .001$).

DISCUSSION

The present study aimed to characterise inter-limb isometric strength symmetry in the upper and lower limbs and to examine the association between handgrip strength and whole-body isometric force production in physically active young adults. The main findings were that: (1) inter-limb asymmetry values for both handgrip and bilateral IMTP variables were low and remained below commonly cited clinical thresholds; (2) no meaningful association was observed between habitual physical activity level and asymmetry magnitude; and (3) handgrip strength demonstrated strong positive associations with IMTP-derived force variables, supporting its potential role as a practical indicator of global isometric strength capacity.

As expected, males exhibited greater absolute isometric strength values than females across both upper- and lower-limb assessments. These findings are consistent with previous literature reporting sex-related differences in maximal force production attributable to variations in muscle cross-sectional area, neuromuscular activation and endocrine profiles (Miller et al., 1993; Hunter, 2014). Importantly, no sex differences were observed in asymmetry magnitude, suggesting that despite disparities in absolute strength, bilateral force distribution strategies during maximal isometric tasks are comparable between males and females in physically active populations (Bishop et al., 2018).

Inter-limb asymmetry values observed in the present study were relatively small for both handgrip and IMTP assessments and did not approach thresholds typically associated with elevated injury risk. Thresholds ranging from 10% to 15% have frequently been proposed in the literature; however, these values are largely derived from unilateral or joint-specific dynamic assessments, particularly in athletic cohorts (Knapik et al., 1991; Bishop et al., 2016). The present findings suggest that in physically active but non-specialised individuals, bilateral isometric force production during multi-joint tasks is characterised by a high degree of

symmetry. This may reflect balanced neuromuscular development associated with general physical activity exposure, rather than the unilateral loading patterns commonly observed in sport-specific training contexts (Guan et al., 2022; Hietamo et al., 2021).

The absence of a relationship between self-reported physical activity level and asymmetry magnitude further supports the notion that overall activity volume alone may not be a primary determinant of inter-limb strength symmetry in non-elite populations. While sport-specific training and repetitive unilateral demands have been shown to influence asymmetry development in athletes (Bishop et al., 2018), the relatively homogeneous and non-specialised activity profiles of the present sample may have limited the emergence of meaningful asymmetry differences. Alternatively, it is possible that qualitative aspects of movement exposure, such as unilateral loading frequency or task variability, play a more influential role than total activity volume (Jones & Bampouras, 2010).

One of the most notable findings of this study was the strong association between handgrip strength and IMTP-derived force variables, including peak force, average force and impulse. Similar associations between handgrip strength and lower-body isometric force production have been reported previously, supporting the concept of shared neuromuscular determinants underlying maximal voluntary force expression (Wind et al., 2010; Rhodes et al., 2022). These shared determinants likely include maximal voluntary activation, central motor drive and neural efficiency, which influence force production across multiple muscle groups during isometric tasks (Suchomel et al., 2018).

From an applied perspective, these findings reinforce the potential utility of handgrip strength as a pragmatic screening tool in settings where comprehensive strength testing batteries are not feasible. Handgrip dynamometry is time-efficient, low-cost and highly reliable, making it attractive for large-scale monitoring or preliminary assessment of general strength status (Bohannon, 2015; Hogrel, 2015). Nevertheless, it is important to acknowledge that handgrip testing cannot replace task-specific assessments such as the IMTP, as it does not capture lower-limb coordination strategies, bilateral force-sharing dynamics, or technical factors inherent to multi-joint force production (Comfort et al., 2019).

Several limitations should be considered when interpreting the present findings. The cross-sectional design precludes causal inference regarding the relationship between inter-limb asymmetry and neuromuscular performance. Additionally, the sample was restricted to students from a single institution, which may limit generalisability to populations with different training histories or activity profiles. The exclusive use of bilateral isometric assessments may also underestimate limb-specific deficits that could be revealed through unilateral testing or electromyographic analysis (Keogh et al., 2020). Finally, the absence of injury history data prevented direct examination of the relationship between asymmetry magnitude and musculoskeletal injury risk, which warrants further investigation.

In conclusion, physically active young adults exhibit minimal inter-limb isometric strength asymmetry in both upper and lower limbs, despite clear lateral dominance. The strong association between handgrip strength and whole-body isometric force production highlights the potential role of handgrip testing as a practical indicator of global isometric strength capacity. Future longitudinal research incorporating unilateral assessments and injury surveillance is required to further elucidate the role of inter-limb symmetry in performance development and injury risk.

CONCLUSION

This study demonstrated that physically active young adults exhibit minimal inter-limb isometric strength asymmetry in both the upper and lower limbs when assessed using handgrip dynamometry and the bilateral isometric mid-thigh pull. Despite clear lateral dominance, asymmetry magnitudes remained well below commonly cited clinical thresholds and were not influenced by habitual physical activity level.

A key finding was the strong association between handgrip strength and whole-body isometric force production, supporting the use of handgrip testing as a practical and time-efficient indicator of global isometric strength capacity in physically active populations. However, task-specific assessments such as the IMTP remain essential for a detailed evaluation of lower-limb force production and bilateral force-sharing strategies.

Collectively, these findings contribute to a better understanding of inter-limb strength symmetry during bilateral isometric tasks and support the complementary use of simple and comprehensive strength assessments in applied sport and exercise science settings. Future longitudinal research incorporating unilateral testing and injury surveillance is warranted to further clarify the role of inter-limb symmetry in neuromuscular performance and injury risk.

Limitations

Limitations include the restriction of the sample to a single institution, the cross-sectional design preventing causal inference and the exclusive use of isometric testing, which does not capture dynamic performance qualities. Additionally, the lack of historical injury data prevents direct correlation between current strength deficits and injury history.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows:

Conceptualisation: Morales Emmanuel. Methodology: Morales Emmanuel; Marco Ramos; Ezequiel Aquistapace. Formal analysis: Morales Emmanuel. Investigation: Morales Emmanuel; Leandro Nodari; Marco Ramos. Data curation: Morales Emmanuel. Writing – original draft: Morales Emmanuel. Writing – review & editing: Morales Emmanuel; Dario Cappa. Supervision: Dario Cappa. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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