

Comprehensive assessment of bilateral knee extensor strength asymmetry in healthy nonathletes using torque–angle relationships

MARIA GANEVA¹, RADOSLAV MAVREVSKI², KATERINA STAMBOLIEVA³, PETER MILANOV⁴, NEVENA PENCHEVA⁵

^{1,5}Department of Anatomy and Physiology, Faculty of Public Health, Health Care and Sports, South-West University “Neofit Rilski”, Blagoevgrad, BULGARIA

^{2,4}Department of Informatics, Faculty of Mathematics and Natural Sciences, South-West University “Neofit Rilski”, Blagoevgrad, BULGARIA

^{1,3}Institute of Neurobiology, Bulgarian Academy of Sciences, Sofia, BULGARIA

⁴Institute of Mathematics and Informatics, Bulgarian Academy of Sciences, Sofia, BULGARIA

Published online: November 30, 2023

(Accepted for publication : November 15, 2023)

DOI:10.7752/jpes.2023.11338

Abstract

Problem statement: Bilateral assessment of knee strength is crucial for identifying and understanding lower limb strength asymmetry. However, there is a scarcity of data in the literature regarding the bilateral strength asymmetry of knee extensors in healthy, untrained individuals, particularly in relation to a limited number of tested positions. **Aims:** 1) To investigate and quantify the bilateral knee extensor strength asymmetry between the dominant (DL) and non-dominant leg (NDL) in nonathletes. 2) To utilize dynamometric measurements to assess isometric peak torque (PT) across the full range of motion. 3) To apply an optimal mathematical function for modelling the torque–angle relationship, allowing a detailed examination of the respective curves for both legs using the bilateral asymmetry index (BAI). **Methods:** Isometric peak torque (PT) was measured using isokinetic dynamometry (Biodex 4Pro) in a cohort of 12 male nonathletes (age of 26 ± 7 years, height of 1.8 ± 0.1 m, and body mass of 78 ± 10 kg). Measurements were taken at various positions ($^{\circ}$): 20, 40, 60, 70, 80, 90, 100, and 110. The data were modelled with rational function, established to be the optimal and the obtained torque-angle curves were grouped in three asymmetry patterns, based on the BAI values and the behaviour of the DL and NDL curves. The physical activity of nonathletes was evaluated as a sum of points for current weekly exercise and for sport training in the childhood-adolescent age. **Results:** The first pattern presents low levels of bilateral asymmetry (with $BAI < 15\%$) in the whole range of motion. The second one demonstrate high asymmetry in the angular range 80° - 110° (BAI up to 27%), while in the third pattern, asymmetry was observed in both ranges: 20° - 40° (BAI between 28 -31%) and 90° - 110° (BAI up to 26.4% and 39.7% in the range of optimal or close to optimal muscle length). Particular for the third pattern was: - a rightward shift of the maximal PT in the knee joint torque-angle curve only in the DL; - a stronger NDL in the range where extensors are shorter; and - a highest score for the level of physical activity. **Conclusions:** These results pointed out that leg dominance appears to form different motor skills of knee extensors, which can result in strength asymmetry variations in nonathletes. Therefore, we recommend paying attention to knee extensors strength diagnostics in nonathletes. Thus, based on the results from this research, we suggest a minimum of two knee positions for bilateral asymmetry evaluation in healthy men, one of which at shortened extensors in the range 30 - 50° and one at lengthened in the range 80 - 90° .

Key Words: Bilateral Strength Asymmetry, Torque-Angle Curves, Nonathletes, Knee Extensors

Introduction

Interlimb asymmetry has been an essential aspect of research in physiology of the asymmetry of the brain hemispheres and the so-called cerebral lateralization, which are object of increasing interest in scientific areas related with sport sciences, exercise physiology, biomechanics, physiotherapy, etc. (Przybyla et al., 2011; Sainburg et al., 2016). Bilateral asymmetry has been evaluated through numerous single-limb balance, range of motion, strength, and stability tests for risk identification, performance improvement, and rehabilitation goals in clinical practice as assessments of limb function. These quantitative assessments are often represented by: jump asymmetry tests (Michailidis et al., 2020), star excursion tests or Y-balance tests (Stiffler et al., 2017; González-Fernández et al., 2022; Tsvetkova-Gaberska & Pencheva, 2022) and isokinetic or isometric strength tests as well (Dai et al., 2019; Daneshjoo et al., 2023). Their usage in clinical and sports practice is constantly changing as a result of ongoing evaluations by practitioners, physicians, and researchers.

Bilateral assessment of knee strength is widely used to determine the magnitude of interlimb strength asymmetry (Dai et al., 2019; de Lira et al., 2017), to establish relationships between the degree of strength asymmetry and injury susceptibility (Daneshjoo et al., 2023), as well as during rehabilitation after injury and

return-to-sport decisions (Grindem et al., 2016; Brunst et al., 2021). Strength measurement by isokinetic dynamometry has established itself as the gold standard for determining the strength characteristics of a group of muscles involved in the movements of a given joint (Drouin et al., 2004; Martin et al., 2006; Stark et al., 2011; Tuominen et al., 2023). The isokinetic dynamometry allows the comparison of strength parameters of a group of muscles in isometric mode, where the maximal voluntary contractions are measured in both limbs, which allows the assessment of bilateral asymmetry, and the torque-angle relationships, as well (Kubo et al., 2006; Hahn et al., 2011).

There are numerous coefficients suggested in the literature for calculating bilateral asymmetry, presented either by bilateral asymmetric index (BAI) or interlimb symmetry index (Parkinson et al., 2021). It is widely accepted that a large asymmetry in function or performance between limbs can be dangerous, but the literature describing the impact of asymmetry on the risk and performance is rather contradictory (Bishop et al., 2017; Bishop et al., 2018; Parkinson et al., 2021). Some authors suggest that 10% is the barrier between low and high bilateral strength asymmetry (Grindem et al., 2016; O'Malley et al., 2018), or even 5% (Croisier et al., 2008), while others consider as normal the values up to 15% (Knapik et al., 1991; de Lira et al., 2017). Even though the bilateral asymmetry is actively studied in athletes and patients, there is a lack of sufficient data for healthy nonathletes. In the current research we are focusing on the examining of the lower limb asymmetry in healthy subjects, who do not actively play organised sports. Understanding the role of limb dominance on strength asymmetry could also be beneficial when the values of the BAI in healthy nonathletes are used as study controls. In the relevant literature on bilateral strength differences of knee extensors in healthy nonathletes, the dominant limb (DL) is considered to either generate higher or equal force moment, as compared with the non-dominant limb (NDL) (de Ruiter et al., 2009; Lanshammar & Ribom, 2011). Additionally, there is conflicting information in the literature regarding how the DL and NDL contribute to interlimb differences (Kong & Burns, 2010; Lanshammar & Ribom, 2011). We hypothesize that healthy people, who do not participate in systemic and specific sports activities, but have variations in the level of physical activity, develop different strength profiles of the DL and NDL, and angle-specific differences in interlimb asymmetry degree. It is not clear to what extent these differences exceed the BAI range in the untrained, which is not beneficial when higher than 15% (Kannus, 1994).

The main parameter for evaluation of strength asymmetries is the peak torque (PT) generated by a certain muscle group. The isometric mode of measurement allows to change the angle and to establish the knee position, where the length of the muscles is optimal and the registered torque is the PT. The most commonly used angular position for isometric testing of knee extensors appears to be the 90° (Hotta et al., 2007; de Souza-Teixeira et al., 2009; Lisee et al., 2018; Leporace et al., 2023). Because knee extension muscles are at resting starting length and their sarcomeres are in ideal overlap, this position frequently results in maximal force output. However, limiting measurements to the 90° knee position is not always helpful and may result in incomplete or incorrect conclusions during isometric interlimb asymmetry testing of knee extensors. In our perspective, the varied and restricted number of tested positions, which typically involve only a portion of the knee range of motion, contribute to the asymmetry discrepancies in the literature. Consequently, the most complete and comprehensive information on the isometric strength and bilateral strength asymmetry of the knee joint could be achieved by testing many positions of the range of motion and generating torque-angle curves for DL and NDL, which fit the experimental data with an optimal mathematical model (Marginson & Eston, 2001; Kubo et al., 2006; Hahn et al., 2011; Kanelov et al., 2016; Mavrevski, 2014; Milanov et al., 2018). To the best of our knowledge, there is a limited number of studies that test a wide range of motion bilaterally in the knee (Kubo et al., 2006; Kong & Burns, 2010). Furthermore, Kubo et al., 2006 state that there was a great variation in the knee joint torque-angle curves among the tested subjects. In our opinion the generation of individual torque-angle curves would better depict the role of DL and NDL in asymmetry origin, rather than the averaged one.

Therefore, the current study aims: - to investigate the bilateral strength asymmetry of the knee extensors of the DL and NDL in healthy nonathletes, using dynamometric measurement of the PT in isometric mode in the full range of motion; - to establish the optimal mathematical function for modelling of the torque-angle relationship and to generate curves that fit the experimental data; and - to employ BAI and examine the behavior of DL and NDL curves for analysis of the bilateral asymmetry in the whole knee range of motion in healthy, male nonathletes.

Material & methods

Participants and anthropometry

The experiments were approved by the university ethical committee and conducted in the Center for functional research in sports and kinesitherapy at South-West University, Blagoevgrad. Twelve healthy male nonathletes (mean $\pm$ SD: age - 26 ± 7 years, height - 1.8 ± 0.1 m, body mass - 78 ± 10 kg), were considered to be suitable for the current research. The criteria for participation involved evaluation of weekly physical activity and overall health, lack of any trauma on the lower limbs, as well as no involvement in sport related activity after the age of 18 years. Participants signed written informed consent, after familiarizing themselves with the conditions, type and method of conducting the functional measurements. Anthropometric characteristics were

measured by a bio impedance analyzer (Ioi 353) and the following parameters were registered: height (cm), body mass (kg), body mass index (BMI, kg/m^2), soft lean mass (SLM, kg), mass of body fat (MBF, kg), percentage of body fat (PBF, %) and a segmental analysis of the lower limbs, involving SLM and MBF of each leg. The subjects were instructed not to consume food or beverages before the measurement and not to exert themselves excessively the day before. The testing was conducted with minimal clothing and without any metals on the participants' body. The level of physical activity of the examined subjects was evaluated as a sum of points for their current weekly exercise and points for sport training in childhood-adolescent age of a certain type of sport.

Test protocol with isokinetic dynamometer

The lower extremity dominance was determined with a question about the preferred leg to kick a ball. The preferred leg was assigned as DL and the other as NDL. Isometric PT was measured with isokinetic dynamometer (Biodex 4Pro). Maximal isometric contractions were performed in the following eight knee angle positions ($^{\circ}$): 20, 40, 60, 70, 80, 90, 100 and 110 (with 0° being full knee extension), with two repetitions for



Fig. 1. Positioning of a participant for dynamometric testing of the knee extensors.

each leg. Two repetitions were used instead of three or more to prevent muscle fatigue. All participants were instructed not to engage in vigorous physical activity two days before the dynamometric testing. Each individual was given a specific date and time to conduct the isometric testing, as each test took approximately an hour and a half to complete. All subjects performed standardized warm up on a cycle ergometer for a period of 5 min, with 60 W resistance, at 60 rpm pace. Prior to testing, the investigated subjects were familiarized with the test protocol and given a chance to practise isometric contractions at a specific knee position. To measure the strength characteristics of the knee, the dynamometer was oriented at 90° and tilted at 0° . The seat was placed at 90° and the seatback was tilted at 85° . Subjects were seated on the dynamometer chair and secured with shoulder, waist and thigh straps to limit any undesired movement. The knee attachment was fixed to the dynamometer. The dynamometer was adjusted for each participant so that the input shaft was centered at the axis of rotation at the knee that is located through the lateral femoral condyle on the sagittal plane. The knee attachment was adjusted so that it was proximal to the lateral malleolus and secured with a strap (Fig.1). The examined subjects were asked to initiate and maintain a maximal muscle contraction in the direction of knee extension for a period of 3 s. Two muscle contractions were performed for each knee angular position, with 30 s rest time in between. Relaxation time between positions was set to 90 s. The eight knee positions were performed in randomized manner. The two knee joints were tested sequentially. The resulting isometric PT was registered in Nm.

Data processing, mathematical modelling and statistics

After selection of the higher torque value between the two isometric measurements for each angle (in Nm), we applied the descriptive statistics to evaluate for each knee angle, of the eight chosen, the mean value and standard error of the mean for the healthy nonathletes. The standard error of mean instead of the standard deviation was used, because this study deals with the mean torque-angle curves, where the SEM allows to illustrate the accuracy of the established mean curves. For all anthropometric measurements were assessed means $\pm$ SD values, coefficient of variation and upper and lower limit of the confidence interval. The normality of the distribution was checked with the Shapiro-Wilk test ($p < 0.05$). The availability of bilateral isometric measurements allowed to calculate the BAI. BAI was calculated as the ratio between the peak torque (Nm) of the extensors of the DL and NDL in percentages by the formula: $((\text{PT of stronger leg} - \text{PT of weaker leg}) / \text{PT of stronger leg}) * 100$ (Lockie et al., 2012). Since the size of the sample was less than 30 participants, the differences between the anthropometric and dynamometric parameters of DL and NDL and between the level of physical activity between the pattern subgroups were evaluated with the Mann-Whitney U test ($p < 0.05$) and Kruskal-Wallis test with Dunn's post-hoc test, used to compare PT differences between DL and NDL at $p < 0.05$.

In order to find the most proper type of mathematical function for modelling of the strong, non-linear torque-angle relationships, we explored the rational functions, which are a ratio of two polynomials. Using the least squares method and Akaike Information Criterion (Mavrevski, 2014; Milanov et al., 2018) we examined various rational functions, including functions of different degrees in the numerator and the denominator, and found the type providing the best approximation of the experimental torque-angle data. This optimal model is

presented with the following equation: $Y = (a + c \cdot \ln(x) + e \cdot (\ln(x))^2) / (1 + b \cdot \ln(x) + d \cdot (\ln(x))^2 + f \cdot (\ln(x))^3)$, which was used to fit the experimental data and to generate torque-angle curves.

The processing of the obtained data with descriptive statistics, the application of the method of least squares in the regression analysis and curves fitting and the assessment of the differences in mean values, were performed with GraphPad Prism software package (Ver. 3.0). A significance level of $p < 0.05$ was assumed.

Results

The anthropometric and body mass characteristics of the participants are presented in Table 1 as mean values, standard deviations, coefficients of variation, and 95 % confidence intervals. Because of the high values of the coefficients of variation, the group of tested individuals is heterogeneous, concerning the variables: age (the range is 19-39 years), MBF and PBF, and also for the fat mass and fat percentage, measured separately for DL and NDL. According to the Shapiro-Wilk test, all measured characteristics have a normal distribution ($p < 0.05$), except the age. BMI values and fat criteria such as MBF and PBF are borderline overweight, however, the mean value of SLM (56.66 ± 5.97 ; Table 1) is close to the reference values. The right leg was dominant in ten of the twelve subjects investigated. No differences were found between DL and NDL in terms of both MBF and SLM (Mann Whitney U test, $p < 0.05$).

Table 1. Descriptive statistics of the studied anthropometric and body composition parameters in healthy non-athletes

Anthropometric and body mass parameters	Mean $\pm$ SD	V (%)	95% CI (upper and lower)
Age (years)	25.75 $\pm$ 7.20	27.96	21.18 – 30.31
Height (m)	1.77 $\pm$ 0.09	4.82	1.71 – 1.82
Body weight (kg)	78.23 $\pm$ 10.05	12.84	71.84 – 84.61
Body mass index (kg/m ²)	25.12 $\pm$ 2.81	11.19	23.33 – 26.90
Mass of body fat (kg)	17.88 $\pm$ 5.40	30.23	14.44 – 21.31
Percentage of body fat (%)	21.38 $\pm$ 6.05	28.28	17.54 – 25.23
Soft lean mass (kg)	56.66 $\pm$ 5.97	10.54	52.86 – 60.45
Mass of body fat DL (kg)	3.04 $\pm$ 1.12	36.73	2.33 – 3.75
Soft lean mass DL (kg)	10.33 $\pm$ 1.07	10.34	9.65 – 11.01
Mass of body fat NDL (kg)	3.06 $\pm$ 1.14	37.14	2.34 – 3.78
Soft lean mass NDL (kg)	10.24 $\pm$ 1.07	10.42	9.57 – 10.92

Abbreviations: SD - standard deviation; V- coefficient of variation; DL - dominant limb; NDL - non-dominant limb; CI - confidence interval.

Nonlinear torque-angle relationships of the knee extensors for DL and NDL, modelled with a rational function as curves, are demonstrated in Fig. 2, where the values of the calculated BAI, that are also presented, concerns the curves with means $\pm$ SEM and the curves of typical examples.

Three main patterns of relation between the curves of DL and NDL were detected. From the first torque-angle curve pattern (Fig. 2 - first pattern), which was observed in 25% of the subjects ($n=3$), reveal the following tendencies: - low levels of bilateral asymmetry ($BAI < 15\%$), due to small strength differences between the extensors of the DL and NDL in the whole tested range of motion (20° - 110°), where both curves are closely located and the maximal PT has similar values for both limbs, which are 280 ± 27 Nm at 90° for DL and 293 ± 40 Nm at 80° for NDL; - the curves of DL and NDL with means $\pm$ SEM indicate an increase of the PT values in the range 20° - 70° ; - the generation of maximal PT (the highest PT value from the tested range, where the knee extensors length is optimal) in the area 80° - 90° and a decrease of the torque values in the range 100° - 110° , where the muscles length is maximal. The torque-angle curves of both limbs and the values of BAI of a separate participant, are presented as a typical example of the first pattern in Fig. 2 also, as an illustration for the subjects in which this pattern is established.

In the second torque-angle relationship pattern, observed in 42% of the participants ($n=5$), the knee extensors of DL are rather stronger as compared with those of NDL in the range of the joint angle of 80° - 110° (Fig. 2, second pattern), where the BAI is more than 15%, but the bilateral asymmetry is most pronounced in the 90° and 100° angles. This is evident both from the curve with means $\pm$ SEM, and from the typical example of this pattern, in which BAI in 90° and 100° is 24.6% and 27.1%, respectively. No significant differences were proven between the PT of DL and NDL in the participants with this pattern at all angular positions (Kruskal-Wallis test, Dunn's post-hoc test, $p < 0.05$). The maximal PT of the extensors, where their length is optimal, does not exceed 269 Nm and 221 Nm in DL and NDL, respectively.

The third pattern of the torque-angle relationship has the following features (Fig. 2, third pattern): - the extensors of the NDL generate higher PT values as compared with DL in the range between 20° to 70° , which are not observed in the other two patterns; - although the differences are not statistically significant ($p < 0.05$, Kruskal-Wallis test, Dunn's post-hoc test), the values of BAI in curve with means $\pm$ SEM at 40° reach 23.7 %; - the extensors of DL produce greater PT values from that of NDL in the range 80° to 110° , similar to the behaviour of the second pattern curves; and - the maximal PT, where the length of the muscles is optimal, is generated at different knee angular position for the both limbs, with higher maximal PT values of the DL ($314 \pm$

10 Nm at 90°) as compared with NDL (289±22 Nm at 80°), although the differences were again not statistically significant. All specified peculiarities create an opportunity for generation of the bilateral strength asymmetry in both ranges: - 20-40° (where the knee extensors are shorter) with values of BAI in the curve of the typical example - 28.2% and 31.3 % in 20° and 40°, respectively; and - 90°-100° (where the extensors are with optimal or close to the optimal length) with values of BAI -16% and 28% in curves with means ± SEM or in curves of the typical example - 26.4% and 39.7 %, respectively. The third torque-angle pattern is typical for 33% of the participants (n=4).

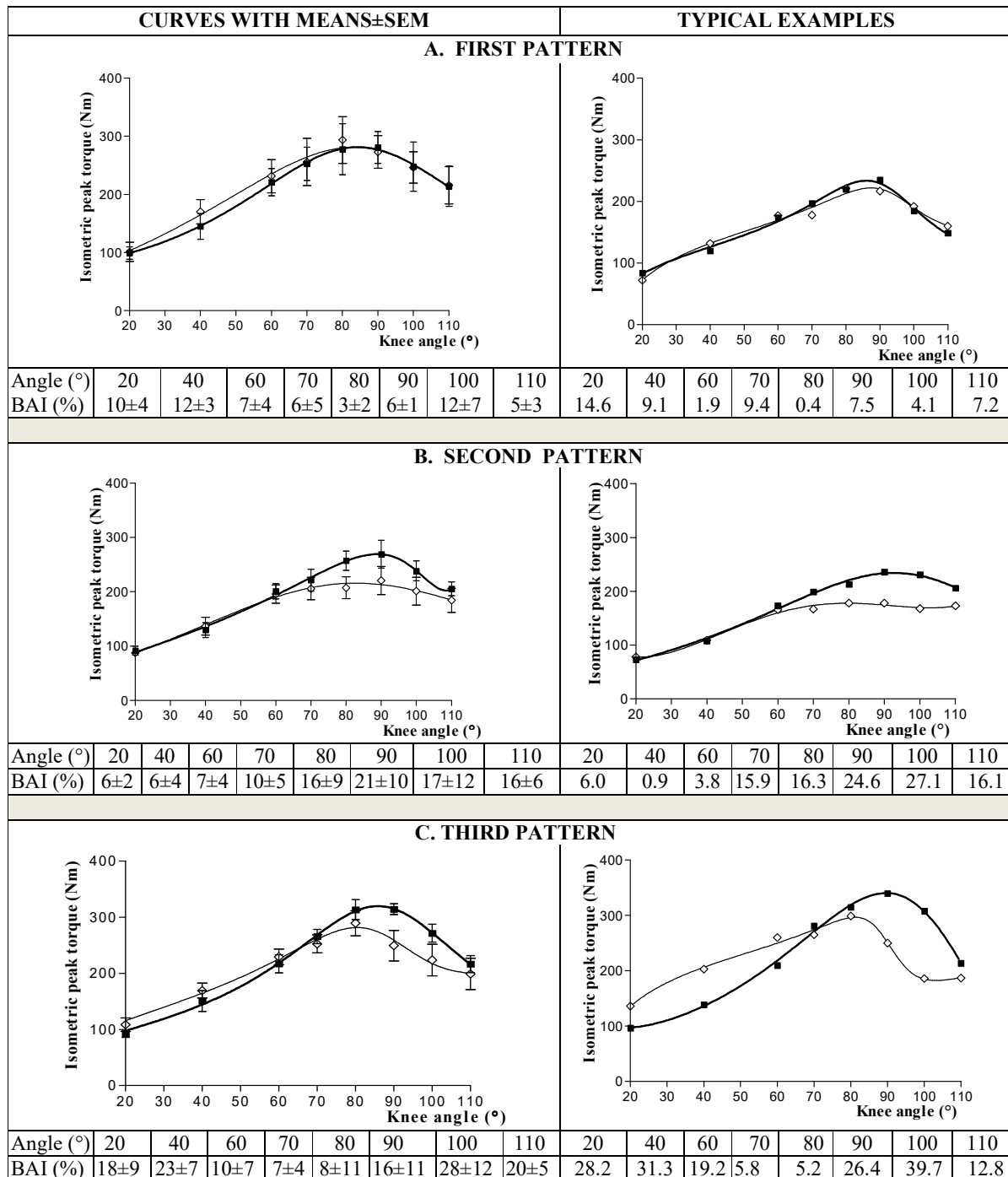
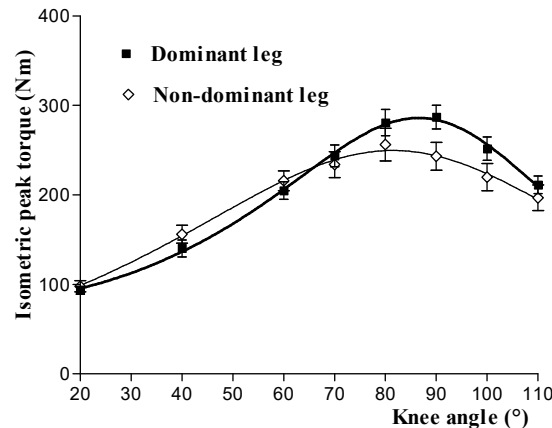


Fig. 2. Torque-angle relationships of the knee extensors of dominant and non-dominant leg in healthy non-athletes, distinguished in three patterns with respective typical examples, and values of bilateral asymmetry index (BAI). Designations: ■ - dominant limb; ◇ - non-dominant limb.

The torque-angle curve, generated using the values of means $\pm$ SEM of PT of all tested participants, is demonstrated in Fig. 3. All of the subjects achieved their maximal PT at the range of knee angle 80-90°. At this range the DL shows higher PT than the NDL in 67% of the tested men. Moreover, this torque-angle curve indicates that the maximal PT of DL (287 ± 46 Nm), achieved at the optimal length of the extensors, is produced at knee position at 90°, while that of NDL (256 ± 63 Nm) was at 80°. Further, no statistically significant differences were found between the PT of DL and NDL at all angular positions (Kruskal-Wallis test, Dunn's post-hoc test, $p < 0.05$) and the BAI is increased slightly above 15% only in the region of the optimal length of the extensors (90°-100°), where the maximum PT of DL is generated.



Angle (°)	20	40	60	70	80	90	100	110
BAI (%)	11.2 $\pm$ 8	12.9 $\pm$ 9	7.5 $\pm$ 5	8.1 $\pm$ 5	9.9 $\pm$ 10	15.5 $\pm$ 10	19.7 $\pm$ 12	14.5 $\pm$ 8

Fig. 3. Mean ($\bar{x} \pm$ SEM) torque-angle relationships of the knee extensors of dominant and nondominant leg in healthy nonathletes and values ($\bar{x} \pm$ SD) of bilateral asymmetry index (BAI) in all tested angle positions.

The scoring of the level of physical activity for the participants, in which the third torque-angle relationship pattern between DL and NDL is observed, was 24.5 ± 4.4 points. This value was significantly higher ($p < 0.05$) as compared with those of the first (5.3 ± 3.5 points) and second (15.0 ± 3.7 points) pattern and the score of the participants from the second pattern was greater than that of the first (Mann-Whitney U test). In addition, among the subjects, in which the first or the second pattern was observed, only one played sports in childhood and adolescence, while from those who displayed the third pattern, only one did not play sports.

Discussion

Basically, we aimed to investigate the bilateral strength differences of knee extensors in untrained males through the entire range of motion of the joint, in which to calculate the asymmetry indices as well. So, we applied isokinetic dynamometry at eight knee angular positions and generated torque-angle curves, that fit the data with nonlinear, rational function. The results revealed that: (i) the individual torque-angle curves of DL and NDL of knee extensors in nonathletes, could be differentiated in three main patterns of interaction and different levels of bilateral strength asymmetry, assessed with the measure BAI; (ii) the first pattern concerns low levels of bilateral strength asymmetry ($BAI < 15\%$) in the full range of motion, the second one reveal asymmetry in the angular range 80°-110°, while in the third pattern, asymmetry was observed in both ranges: 20°-40° and 90°-110°; and (iii) the BAI is a more sensitive criterion for assessment of bilateral strength asymmetry as compared with statistical tests for evaluation of the significant differences in the peak torque between DL and NDL.

The age range (19-29 years) of the investigated subjects was wide and their height and body mass were relevant for men. Although, the values of BMI and fat criteria (MBF and PBF) were borderline overweight, they were not too fat, for untrained people with not high levels of physical exercise. Nevertheless, the values of the SLM, which is a criterion for muscle mass, were within the referent interval (Kirk et al., 2021), which is in accordance with the high values of PT and maximum PT, generated by the knee extensors of DL and NDL of the subjects investigated. Since there were not differences in the parameters MBF and SLM between the two legs (Mann Whitney U test, $p < 0.05$), the further established strength profile differences between them cannot be attributed to changes in body mass composition, but rather to the effect of limb dominance on the muscular functional performance, including in walking (McGrath et al., 2016; Polk et al., 2017).

The structural and functional asymmetry of human body is genetically predisposed from the asymmetry of the brain hemispheres and their specialization, which are fundamental features of the brain organization (Bisiacchi & Cainelli, 2022). Moreover, cerebral lateralization is a marker of successful development (Liu et al., 2009). The assessment of the interlimb strength asymmetry has been an essential aspect of research in different

scientific areas such as physiology and motor control, biomechanics, physiotherapy and prevention of injuries, sport sciences, etc. (Thomas et al., 2020; Kalata et al., 2020; Ebert et al., 2021; Sarro et al., 2022; Afonso et al., 2022). The evaluation of the bilateral asymmetry in healthy nonathletes, although not well studied, is relevant and useful, especially when it concerns: - the judgement of the differences between athletes and untrained individuals as a criterion for exercise-induced adaptations in skeletal muscles (Trezise & Blazevich, 2019); and - assessment of the interlimb asymmetry in sport disciplines with predominantly asymmetric types of locomotion, which generate different manner of exercise of the kicking and supporting leg, such as football (Gonzalo-Skok et al., 2019; Bishop et al., 2022). The data obtained in the present study prove that in healthy untrained men different patterns of asymmetry are observed, some of them with a high percentage of BAI. The calculation of BAI of knee extensors, using the stronger and the weaker limb, according to the formula of Lockie et al., (2012) is proved to be more efficient than using dominant and non-dominant or injured and uninjured limb, because the beforehand assumption that the DL is stronger than the NDL, according to our results, is not always true for the knee full range of motion. Parkinson et al., (2021) also recommend this approach in order to avoid false asymmetry indices.

The core of this research is the assumption that, at different angular positions of the knee joint, the length of the extensors and of the so-called moment arm change and it is not clear to what extent the bilateral force asymmetry in healthy nonathletes remains within normal limits throughout the full knee range of motion. The results of this study show, that along this range, the bilateral asymmetry changes not only as a value, but also as a ratio between DL and NDL. In fact, in the angular range of the shortened extensors, NDL can generate either higher or similar PT values, as compared to those of the DL, while in the range of optimal or longer extensor lengths, only DL is observed to be stronger. This finding is consistent with the research of Ebert et al. (2021), where in testing knee extensors in isokinetic, concentric mode, it was found that asymmetry differs depending on the angle at which a separate measure is taken throughout the isokinetic torque range of motion and shows high asymmetry values, even when isokinetic testing detects low asymmetry. Beere et al. (2022) test strength asymmetry in isometric mode of knee extensors in positions 30°, 60° and 90° and suggest both angles 30° and 90° to be suitable for detecting asymmetries after ACL reconstruction. The results of the study, accomplished by us, on extensors asymmetry in the knee, support this suggestion and prove that it should be considered full or at least larger range of motion of the joint, because the isolated assessments of PT and asymmetry miss the strength deficit and the presence of asymmetry.

A novel approach was applied during this investigation to establish the strength asymmetry of the extensors in the full range of motion of the knee joint. Thus, torque-angle curves of DL and NDL were generated through which the torque differences were visualized, and the calculated asymmetry indices in all measured angular positions proved that the interlimb strength asymmetry of the knee extensors was not constant across the entire range of the motion. The majority of studies on the non-linear torque-angle relationships of the knee extensors have been modelled with polynomials without aiming for optimality of the models (Carvalho, 2015; Parkinson et al., 2022). In the present study, the experimental data were modelled with a rational function, the optimality of which was proven with relevant criteria. This allowed an adequate extrapolation of the data, which provided a good visualization of the differences between the torque-angle curves of the DL and NDL, especially with no statistically significant differences in the peak torque, but with differences in BAI in some of the joint ranges of motion. Mean BAI values varied from $7.5 \pm 5\%$ at 60° to $19.7 \pm 12\%$ at 100° knee angle position. Practitioners and researchers should be aware of that, when testing bilateral asymmetries in isometric mode at discrete knee positions, in order to make accurate decisions. Moreover, the asymmetry in our tested group is not minimal between DL and NDL, as expected for healthy individuals, and in many cases exceeds the suggested threshold of 10-15% (Palmieri-Smith & Lepley, 2015; Rohman et al., 2015; Parkinson et al., 2021). This should be taken into account, when healthy subjects participate as study controls. The healthy nonathletes, as subjects of this study, show high heterogeneity of knee extensors asymmetry. Mean BAI values show high SD that range from 5 to 12%, which in the 80° knee position are equal to the BAI value ($9.9 \pm 10\%$). Similar data were shown for jiu-jitsu athletes by Sarro et al. (2022), stating that there was a high variability of the interlimb asymmetry magnitude. McFall et al. (2022) tests elite trials cyclists and concludes that bilateral asymmetry is very highly individual in these athletes.

The key result of this study was the establishment of three pattern relations between the torque-angle curves of DL and NDL of knee extensors in healthy nonathletes, which differ in the presence or absence of bilateral asymmetry and the way it is formed in the full range of motion. An absence of both bilateral asymmetry ($BAI < 15\%$) and of significant differences between the PT of DL and NDL were observed in all angular positions in the first pattern of torque-angle relationship (Kruskal-Wallis ANOVA, $p < 0.05$), which was an expected result for healthy untrained people. However, in many studies in the relevant literature, where healthy nonathletes were examined, the lack of interlimb differences in the knee strength is considered evidence, that there is no bilateral strength asymmetry. Such is the study by Ditroilo et al. (2010), which did not find any difference in maximal voluntary force and rate of force development between dominant and non-dominant knee extensors in a sample of 152 people of various ages. Similar are the results with healthy males of Hotta et al., (2007) and with healthy untrained and trained men and women of Lisee et al., (2018). In sport, based on the same approach, two meta-

analyses found that lower limb dominance did not influence isometric and dynamic muscle strength (McGrath et al., 2016; De Lang et al., 2019). The present study proves that the strength asymmetry index is more sensitive criterion for the assessment of bilateral strength asymmetry than the tests for statistical differences between the strength parameters of DL and NDL.

At the second and third pattern, which were observed in the subjects with a higher score for physical activity, bilateral asymmetry higher than 15% was found, which is either in the angular range 80°-110° or in two ranges - 20°-70° and 90°-100°, respectively. In these ranges, some participants reached BAI values up to 27% in the second pattern. In the third pattern they were between 28 -31% in the shorter lengths range of the extensors and reached up to 26.4% and 39.7% in the optimal or close to optimal muscle length range (Fig. 2, third pattern, typical example). The established highest level of physical activity in the individuals from the third pattern shows that even in some nonathletes, the exercises and more active motor activity, including activities of daily life, create a strength asymmetry, dependent on the leg dominance. It is in accordance with the study of Promsri et al., (2018), where examining bilateral asymmetry in the postural control, using dynamic and static tasks, they established significant differences for variables characterizing asymmetries in the postural accelerations in 26 active young adults, males and females. Further, a specific marker for the third pattern was a rightward shift in the knee joint torque-angle relationship for the DL only, which could be a reason for a high bilateral strength asymmetry in the area of the optimal muscle length of the knee extensors. It is well known, that the rightward shifts in torque-angle curves are related mainly to protective and adaptation changes after an unaccustomed and predominantly eccentric exercises (Mc Hugh & Tetro, 2003; Jakeman & Eston, 2013; Harris-Love et al., 2021). However, in the current study such a shift to the right, albeit weakly, was associated with leg dominance in nonathletes, because it concerns the knee extensors only of the DL. At the same time in the range of the shorter length of the extensors in the participants from the third pattern, NDL was stronger and a high bilateral asymmetry was also observed, according to the measured values of BAI. Similar findings for NDL have been established by Kong & Burns (2010). They investigate healthy recreationally active subjects (men and women), using isometric contractions in multiple knee angle positions and measure higher peak torque values for NDL extensors as compared to the DL at positions 50° and 60°. There are studies, supporting or rejecting the assumption that NDL is the side of choice for balancing the needs of the DL (Promsri et al., 2018; Paillard & Noe, 2020; Gstottner et al., 2009) and is also used to ensure stability. However, NDL work more actively in the range of a weak to moderate knee flexion (20°-70°), being a supporting leg, while the DL is kicking, pushing, initiating walking, running, jumping etc. Thus one leg achieves a motor skill, while the other supports the body mass (Paillard & Noe, 2020). It appears that the leg dominance forms different motor tasks, that can generate force asymmetry in nonathletes. Therefore we recommend paying attention to knee extensors strength diagnostics in nonathletes (Schöllhorn et al., 2010; Thomas et al., 2020).

The torque-angle curves, generated using the means $\pm$ SEM of PT and the respective means $\pm$ SD of BAI, were proved unsuitable for assessing force asymmetry, because the curve tendencies were consistent only with 42% of the tested subjects. But the testing of BAI in a large angular range in many subjects was not routinely applicable. Based on the results from this research, we suggest a minimum of two knee positions for evaluating the bilateral asymmetry in healthy men, one of which with shortened extensors (30-50°) and one in lengthened (80-90°). Additionally, the values and analysis of the PT and bilateral strength asymmetry of the knee extensors in healthy nonathletes, obtained in this study could be used as controls in comparative studies of patients or athletes from different disciplines.

Conclusions

In this study the isometric bilateral strength was measured, using isokinetic dynamometry at eight angular positions of the knee extensors in male nonathletes and the asymmetry indexes were calculated between DL and NDL, through the entire range of motion. The established anthropometric profile differences between both limbs could not be attributed to the changes in body mass composition, but rather to the effect of the limb dominance on the muscular functional performance. The torque-angle curves, generated with nonlinear, rational function, were grouped in three main patterns, according to the relations between DL and NDL and the BAI values. The first pattern concerns subjects with low levels of bilateral strength asymmetry (BAI<15%) in the whole range of motion. In the second one were subjects with a high asymmetry in the angular range 80°-110° (BAI in some participants reached up to 27%), while in those from the third pattern, asymmetry was observed in both ranges: 20°-40° (with BAI between 28 -31%, in the range of the shorter lengths of the extensors) and 90°-110° (with BAI up to 26.4% and 39.7% in the range of optimal or close to optimal muscle length). The specific features of the participants from the third pattern were: - a rightward shift of the maximal peak torque in the knee joint torque-angle curve for the DL only; - a stronger NDL in the range of the shorter length of the extensors; and - the highest score for the level of physical activity. It appears that the leg dominance forms different motor skills, that can generate force asymmetry in nonathletes. Therefore, we recommend paying attention to the knee extensors strength diagnostics in nonathletes. Based on the results from this research, we suggest a minimum of two knee positions for evaluating the bilateral asymmetry in healthy men, one of which with shortened extensors (30-50°) and one in lengthened (80-90°).

Conflicts of interest - The authors have no conflicts of interest to declare.

References:

- Afonso, J., Pena, J., Sa, M., Virgile, A., García-de-Alcaraz, A., & Bishop, C. (2022). Why Sports Should Embrace Bilateral Asymmetry: A Narrative Review. *Symmetry*, **14**(10), 1993.
- Beere, M., Ebert, J. R., Joss, B., & Ackland, T. (2022). Isometric Dynamometry, Dependent on Knee Angle, is a Suitable Alternative to Isokinetic Dynamometry when Evaluating Quadriceps Strength Symmetry in Patients Following Anterior Cruciate Ligament Reconstruction. *The Knee*, **34**, 124–133.
- Bishop, C., Manuel, J., Drury, B., Beato, M., & Turner, A. (2022). Assessing Eccentric Hamstring Strength Using the NordBord: Between-Session Reliability and Interlimb Asymmetries in Professional Soccer Players. *Journal of Strength and Conditioning Research*, **36**, 2552–2557.
- Bishop, C., Read, P., Lake, J. P., Chavda, S., & Turner, A. N. (2018). Interlimb Asymmetries: Understanding How to Calculate Differences from Bilateral and Unilateral Tests. *Strength and Conditioning Journal*, **40**(4), 1–6.
- Bishop, C., Turner, A. N., & Read, P. (2017). Effects of Inter-Limb Asymmetries on Physical and Sports Performance: A Systematic Review. *Journal of Sports Sciences*, **36**(10), 1135–1144.
- Bisiacchi, P., & Cainelli, E. (2022). Structural and Functional Brain Asymmetries in the Early Phases of Life: A Scoping Review. *Brain Structure and Function*, **227**, 479–496.
- Brunst, C. L., Ithurburn, M. P., Zbojniec, A. M., Paterno, M. V., & Schmitt, L. C. (2021). Return-to-Sport Quadriceps Strength Symmetry Impacts 5-Year Cartilage Integrity After Anterior Cruciate Ligament Reconstruction: A Preliminary Analysis. *Journal of Orthopaedic Research*, **40**(1), 285–294.
- Carvalho, H. M. (2015). Multilevel Models for the Analysis of Angle-Specific Torque Curves with Application to Master Athletes. *Journal of Human Kinetics*, **49**, 25–35.
- Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., & Ferret, J. M. (2008). Strength Imbalances and Prevention of Hamstring Injury in Professional Soccer Players: A Prospective Study. *The American Journal of Sports Medicine*, **36**(8), 1469–1475.
- Dai, B., Loyer, J. V., Vertz, C., Hinshaw, T. J., Cook, R. F., Li, Y., & Sha, Z. (2019). Baseline Assessments of Strength and Balance Performance and Bilateral Asymmetries in Collegiate Athletes. *Journal of Strength and Conditioning Research*, **33**(11), 3015–3029.
- Daneshjoo A., Sadeghi, H., Yaali, R., & Behm, D. G. (2023). Comparison of Unilateral and Bilateral Strength Ratio, Strength, and Knee Proprioception in Older Male Fallers and Non-Fallers. *Experimental Gerontology*, **175**(11), 112161.
- De Lang, M. D., Rouissi, M., Bragazzi, N. L., Chamari, K., & Salameh, P. A. (2019). Soccer Footedness and Between-Limbs Muscle Strength: Systematic Review and Meta-Analysis. *International Journal of Sports Physiology and Performance*, **14**, 551–562.
- Ditroilo, M., Forte, R., Benelli, P., Gambarara, D., & De Vito, G. (2010). Effects of Age and Limb Dominance on Upper and Lower Limb Muscle Function in Healthy Males and Females Aged 40–80 Years. *Journal of Sport Sciences*, **28**, 667–677.
- Drouin, J. M., Valovich-mcLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and Validity of the Biodex System 3 Pro Isokinetic Dynamometer Velocity, Torque and Position Measurements. *European journal of applied physiology*, **91**(1), 22–29.
- Ebert, J. R., Edwards, P., Joss, B., Anear, P., Radic, R., & D'Alessandro, P. (2021). Isokinetic Torque Analysis Demonstrates Deficits in Knee Flexor and Extensor Torque in Patients at 9–12 Months After Anterior Cruciate Ligament Reconstruction, Despite Peak Torque Symmetry. *The Knee*, **32**, 9–18.
- González-Fernández, F. T., Martínez-Aranda, L. M., Falces-Prieto, M., Nobari, H., & Clemente, F. M. (2022). Exploring the Y-Balance-Test Scores and Inter-Limb Asymmetry in Soccer Players: Differences Between Competitive Level and Field Positions. *BMC Sports Science, Medicine and Rehabilitation*, **14**(1), 45.
- Gonzalo-Skok, O., Moreno-Azze, A., Arjol-Serrano, J. L., Tous-Fajardo, J., & Bishop, C. A. (2019). Comparison of 3 Different Unilateral Strength Training Strategies to Enhance Jumping Performance and Decrease Interlimb Asymmetries in Soccer Players. *International Journal of Sports Physiology and Performance*, **14**, 1256–1264.
- Gstöttner, M., Neher, A., Scholtz, A., Millonig, M., Lember, S., & Raschner, C. (2009). Balance ability and muscle response of the preferred and nonpreferred leg in soccer players. *Motor control*, **13**(2), 218–231.
- Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple Decision Rules Can Reduce Reinjury Risk by 84% After ACL Reconstruction: The Delaware-Oslo ACL Cohort Study. *British Journal of Sports Medicine*, **50**(13), 804–808.
- Hahn, D., Olvermann M., Richtberg, J., Seiberl, W., & Schwitz, A. (2011). Knee and Ankle Joint Torque-Angle Relationships of Multi-Joint Leg Extension. *Journal of Biomechanics*, **44**(11), 2059–2065.
- Harris-Love, M. O., Gollie, J. M., & Keogh, J. W. L. (2021). Eccentric Exercise: Adaptations and Applications for Health and Performance. *Journal of Functional Morphology and Kinesiology*, **6**(4), 96.

- Hotta, N., Yamamoto, K., Sato, K., Katayama, K., Fukuoka, Y., & Ishida, K. (2007). Ventilatory and Circulatory Responses at the Onset of Dominant and Non-Dominant Limb Exercise. *European Journal of Applied Physiology*, **101**(3), 347–358.
- Jakeman, J. R. & Eston, R. G. (2013). Joint Angle-Torque Characteristics of the Knee Extensors Following Eccentric Exercise-Induced Muscle Damage in Young, Active Women. *Journal of Exercise Science & Fitness*, **11**(1), 50–56.
- Kalata, M., Maly, T., Hank, M., Michalek, J., Bujnovsky, D., Kunzmann, E., & Zahalka, F. (2020). Unilateral and Bilateral Strength Asymmetry Among Young Elite Athletes of Various Sports. *Medicina (Kaunas, Lithuania)*, **56**(12), 683.
- Kanelov, I., Koroleova, G., Milanov, P., Pencheva, N. (2016). Impact of the Joint Angular Position on the Peak Torque of Elbow Flexors and Extensors in Healthy Males. *Research in Kinesiology*, **44**(1), 128–136.
- Kannus, P. (1994). Isokinetic Evaluation of Muscular Performance. *International Journal of Sports Medicine*, **15**(1), 11–18.
- Kirk, B., Hassan, E., Brennan-Olsen, S., Vogrin, S., Bird, S., Zanker, J., Phu, S., Meerkin, J. D., Heymsfield, S. B., & Duque, G. (2021). Body Composition Reference Ranges in Community-Dwelling Adults Using Dual-Energy X-Ray Absorptiometry: The Australian Body Composition (ABC) Study. *Journal of Cachexia, Sarcopenia and Muscle*, **12**(4), 880–890.
- Knapik, J. J., Bauman, C., Jones, B. H., Harris, J., & Vaughan, L. (1991). Preseason Strength and Flexibility Imbalances Associated with Athletic Injuries in Female Collegiate Athletes. *American Journal of Sports Medicine*, **19**(1), 76–81.
- Kong, P. W., & Burns, S. F. (2010). Bilateral Difference in Hamstrings to Quadriceps Ratio in Healthy Males and Females. *Physical Therapy in Sport*, **11**(1), 12–17.
- Kubo, K., Ohgo, K., Takeishi, R., Yoshinaga, K., Tsunoda, N., Kanehisa, H., & Fukunaga, T. (2006). Effects of Series Elasticity on the Human Knee Extension Torque-Angle Relationship in Vivo. *Research Quarterly for Exercise and Sport*, **77**(4), 408–416.
- Lanshammar, K., & Ribom, E. L. (2011). Differences in Muscle Strength in Dominant and Non-Dominant Leg in Females Aged 20–39 Years - A Population-Based Study. *Physical Therapy in Sport*, **12**(2), 76–79.
- Leporace, G., Guadagnin, E. C., Oliveira, L. P. D., Zeitoune, G., Oliveira, T., & Metsavaht, L. (2023). Influence of Age and Gender on Knee and Hip Isometric Strength of Recreational Physically Active Young and Middle-Aged Subjects. *Fisioterapia e Pesquisa*, **30**(2), <https://doi.org/10.1590/1809-2950/e22006823en>.
- de Lira, C. A., Mascarín, N. C., Vargas, V. Z., Vancini, R. L., & Andrade, M. S. (2017). Isokinetic Knee Muscle Strength Profile in Brazilian Male Soccer, Futsal, and Beach Soccer Players: A Cross-Sectional Study. *International Journal of Sports Physical Therapy*, **12**(7), 1103–1110.
- Lisee, C., Slater, L. V., Hertel, J., & Hart, J. M. (2018). Effect of Sex and Level of Activity on Lower-Extremity Strength, Functional Performance, and Limb Symmetry. *Journal of Sport Rehabilitation*, **28**(5), 413–420.
- Liu, H., Stufflebeam, S. M., Sepulcre, J., Hedden, T., & Buckner, R. L. (2009). Evidence from Intrinsic Activity that Asymmetry of the Human Brain is Controlled by Multiple Factors. *Proceedings of the National Academy of Sciences of the United States of America*, **106**(48), 20499–20503.
- Lockie, R. G., Schultz, A. B., Jeffriess, M. D., & Callaghan, S. J. (2012). The Relationship Between Bilateral Differences of Knee Flexor and Extensor Isokinetic Strength and Multi-Directional Speed. *Isokinetics and Exercise Science*, **20**(3), 211–219.
- Marginson, V., & Eston, R. (2001). The Relationship Between Torque and Joint Angle During Knee Extension in Boys and Men. *Journal of Sports Sciences*, **19**(11), 875–880.
- Martin, H. D., Yule, V., Syddall, H. E., Dennison, E. M., Cooper, C., & Sayer, A. A. (2006). Is Hand-Held Dynamometry Useful for the Measurement of Quadriceps Strength in Older People? A Comparison with the Gold Standard Biodex Dynamometry. *Gerontology*, **52**(3), 154–159.
- Mavrevski, R. (2014). Selection and Comparison of Regression Models: Estimation of Torque-Angle Relationships. *Comptes Rendus de l'Académie Bulgare des Sciences*, **67**(10), 1345–1354.
- McFall, D., Lgee, H., & Cushion, E. J. (2022). Jump Test Asymmetry Profiles of Elite Trials Cyclists. *Journal of Physical Education and Sport*, **22**(4), 1033–1040.
- McGrath, T. M.; Waddington, G.; Scarvell, J. M.; Ball, N. B.; Creer, R.; Woods, K., & Smith, D. (2016). The Effect of Limb Dominance on Lower Limb Functional Performance - A Systematic Review. *Journal of Sports Sciences*, **34**(4), 289–302.
- McHugh, M. P. & Tetro, D. T. (2003). Changes in the Relationship Between Joint Angle and Torque Production Associated with the Repeated Bout Effect. *Journal of Sports Sciences*, **21**(11), 927–932.
- Michailidis Y., Savvakis C., Pirounakis V., Mikikis D., Margonis K., & Metaxas T. (2020). Association Between Jump Asymmetry and Reduced Performance in the Change of Direction Tests of Youth Soccer Players. *Journal of Physical Education and Sport*, **20**(3), 1362 – 1368.
- Milanov, P., Koroleova, G., Mavrevski, R., & Pencheva, N. (2018). Curve Fitting Problem: Torque – Velocity Relationship with Polynomials and Boltzmann Sigmoid Functions. *Acta of Bioengineering and Biomechanics*, **20**(1), 169–184.

- O'Malley, E. G., Richter, C., King, E., Strike, S., Moran, K., Franklyn-Miller, A., & Moran, R. (2018). Counter-movement Jump and Isokinetic Dynamometry as Measures of Rehabilitation Status After Anterior Cruciate Ligament Reconstruction. *Journal of Athletic Training*, **53**(7), 687–695.
- Paillard, T., & Noe, F. (2020). Does Monopodal Postural Balance Differ Between the Dominant Leg and the Non-Dominant Leg? A review. *Human Movement Science*, **74**, 102686.
- Palmieri-Smith, R., & Lepley, L. (2015). Quadriceps Strength Asymmetry after Anterior Cruciate Ligament Reconstruction Alters Knee Joint Biomechanics and Functional Performance at Time of Return to Activity. *American Journal of Sports Medicine*, **43**(7), 1662–1669.
- Parkinson, A., Apps, C., Morris, J. C., Barnett, C. T., & Lewis, M. (2021). The Calculation, Thresholds and Reporting of Inter-Limb Strength Asymmetry: A Systematic Review. *Journal of Sports Science and Medicine*, **20**(4), 594–617.
- Parkinson, A. O., Apps, C. L., Felton, P. J. & Lewis, M. G. C. (2022) The effect of measurement angle on approximations of maximum joint torque. *ISBS Proceedings Archive*, **40**(1), 131.
- Polk, J. D., Stumpf, R. M., & Rosengren, K. S. (2017). Limb Dominance, Foot Orientation and Functional Asymmetry During Walking Gait. *Gait & Posture*, **52**, 140–146.
- Promsri, A., Haid, T., & Federolf, P. (2018). How Does Lower Limb Dominance Influence Postural Control Movements During Single Leg Stance?. *Human Movement Science*, **58**, 165–174.
- Przybyla, A., Good, D. C., & Sainburg, R. L. (2011). Dynamic Dominance Varies with Handedness: Reduced Interlimb Asymmetries in Left-handers. *Experimental Brain Research*, **216**(3), 419–431.
- Rohman, E., Steubs, J., & Tompkins, M. (2015). Changes in Involved and Uninvolved Limb Function During Rehabilitation after Anterior Cruciate Ligament Reconstruction: Implications for Limb Symmetry Index Measures. *American Journal of Sports Medicine*, **43**(6), 1391–1398.
- de Ruiter, C. J., de Korte, A., Schreven, S., & de Haan, A. (2009). Leg Dominancy in Relation to Fast Isometric Torque Production and Squat Jump Height. *European Journal of Applied Physiology*, **108**(2), 247–255.
- Sainburg, R. L., Schaefer, S. Y., & Yadav, V. (2016). Lateralized Motor Control Processes Determine Asymmetry of Interlimb Transfer. *Neuroscience*, **334**, 26–38.
- Sarro, K., Petrovna, J., Lara, R., Martins, L., Silva, A., Souza, S., Momesso, I., & Miana, A. (2022). Seasonal Variation of Strength and Power Magnitude and Asymmetry, and Injury Profile of Brazilian Jiu-Jitsu Athletes. *Journal of Physical Education and Sport*, **22**(6), 1346–1355.
- Schöllhorn, W. I., Beckmann, H., & Davids, K. (2010). Exploiting System Fluctuations. Differential Training in Physical Prevention and Rehabilitation Programs for Health and Exercise. *Medicina (Kaunas, Lithuania)*, **46**(6), 365–373.
- de Souza-Teixeira, F., Costilla, S., Ayán, C., García-López, D., González-Gallego, J., & de Paz, J. (2009). Effects of Resistance Training in Multiple Sclerosis. *International Journal of Sports Medicine*, **30**(4), 245–250.
- Stark, T. D., Walker, B. D., Phillips, J. K., René Fejer, & Beck, R. (2011). Hand-held Dynamometry Correlation with the Gold Standard Isokinetic Dynamometry: A Systematic Review. *PM&R*, **3**(5), 472–479.
- Stiffler, M. R., Bell, D. R., Sanfilippo, J., Hetzel, S., Pickett, K. A., & Heiderscheit, B. C. (2017). Star Excursion Balance Test Anterior Asymmetry is Associated with Injury Status in Division I Collegiate Athletes. *Journal of Orthopaedic & Sports Physical Therapy*, **47**(5), 339–346.
- Thomas, C., Dos'Santos, T., Comfort, P., & Jones, P. A. (2020). Effect of Asymmetry on Biomechanical Characteristics During 180° Change of Direction. *Journal of Strength and Conditioning Research*, **34**(5), 1297–1306.
- Trezise, J., & Blazevich, A. J. (2019). Anatomical and Neuromuscular Determinants of Strength Change in Previously Untrained Men Following Heavy Strength Training. *Frontiers in Physiology*, **10**, 1001.
- Tsvetkova-Gaberska, M., & Pencheva, N. (2022). Determination of Lower Quarter Dynamic Balance in Healthy Adults. *Journal of Physical Education and Sport*, **22**(3), 775–781.
- Tuominen, J., Leppanen, M., Jarske, H., Pasanen, K., Tommi Vasankari, & Jari Parkkari. (2023). Test-Retest Reliability of Isokinetic Ankle, Knee and Hip Strength in Physically Active Adults Using Biodex System 4 Pro. *Methods and Protocols*, **6**(2), 26–26.