©Journal of Sports Science and Medicine (2020) **19**, 745-752
http://www.jssm.org

Research article

Inter-Limb Asymmetries in Volleyball Players: Differences between Testing Approaches and Association with Performance

Žiga Kozinc[1,2] and Nejc Šarabon [1,3,4]✉
[1] University of Primorska, Faculty of Health Sciences, Izola, Slovenia;[2] University of Primorska, Andrej Marušič Institute, Koper, Slovenia; [3] InnoRenew CoE, Human Health Department Izola, Slovenia; [4] S2P, Science to practice, Ltd., Laboratory for Motor Control and Motor Behavior, Ljubljana, Slovenia

Abstract

In this study, we investigated the prevalence of inter-limb asymmetries in young volleyball players and assessed the differences in the outcomes of different strength and power tests. The study sample comprised of 54 young volleyball players (25 males). Both limbs were tested for single-leg jumping for distance (forward and lateral single jump and triple jump forward for distance), single-leg vertical counter-movement jump (CMJ), change-of-direction (CoD) ability with 90 and 180° turn tests, unilateral maximal isometric knee extension torque, rate of torque development (RTD), and rate of torque development scaling factor (RTD-SF). For all tests, inter-limb asymmetry indexes were calculated. The average magnitude of the inter-limb asymmetries varied substantially (2.0-31.2 %) among different outcome measures. The agreement in the categorization of participants into ''symmetrical'' or ''asymmetrical'', based on the >10% threshold, was very poor in general, with the exception of the outcomes within the same task (e.g. CMJ power and CMJ force). Similar findings were found for the agreement on the direction of the asymmetries. Inter-limb asymmetry in RTD-SF was weakly associated with the CoD performance ($r = 0.30$; $p = 0.031$). Multiple strength and power testing protocols are needed to obtain a comprehensive overview of athlete's imbalances. The commonly accepted 10 % threshold for classification of individuals as asymmetrical should be reconsidered and reinvestigated. RFD-SF is suggested as a novel outcome measure that can provide additional information to researchers and coaches.

Key words: Muscle imbalance, volleyball performance, jumping performance, muscle quickness.

Introduction

Volleyball has been a popular sport for a long time, and its popularity continues to grow (Seminati and Minetti, 2013). Despite the non-contact nature of the gameplay, volleyball players nevertheless sustain a fair amount of injuries (Baugh et al., 2018; Keller et al., 2018; Kilic et al., 2017; Seminati and Minetti, 2013). Inter-limb asymmetries have been identified as a potential factor that may contribute to impaired sports performance (Bishop et al., 2018) and possibly increase injury risk (Croisier et al., 2008; Mokha et al., 2016). Therefore, regular assessment of inter-limb asymmetries should be a part of the strength and conditioning programs. Previous research has focused predominantly on investigating upper limb asymmetries in volleyball players, notably the inter-limb asymmetries in shoulder strength and flexibility (Hadzic et al., 2014; Keller et al., 2018; Seminati and Minetti, 2013). However, lower-limb injuries represent a considerable number of volleyball injuries (Kilic et al., 2017) and research in this field is currently lacking. The high incidence of lower-limb injuries in high school and collegiate volleyball players (Pollard et al., 2011) argues strongly for the inclusion of comprehensive routine assessment and integration of preventive intervention in early age, which is in line with the models for counteracting the negative effects of early sport specialization (Myer et al., 2015).

Previous investigations have shown that 27-34 % of basketball and volleyball players exhibit an asymmetry greater than 15 % in vertical jump height (Fort-Vanmeerhaeghe et al., 2016). Another study investigating male volleyball players reported a high (11.24 %) mean inter-limb asymmetry index in knee extensor isokinetic strength at 60°/s, however, the mean index significantly dropped to (5.28 %) at 180°/s, showing inter-limb asymmetries may be contraction velocity-dependent (Schons et al., 2019). Similar findings were reported by Cheung et al. (2012), who showed higher (9.1 %) inter-limb asymmetries during isokinetic knee extension testing at 60°/s, compared to 300°/s (5.4 %), while the results were similar for both velocities for hamstring muscles (4.8-5.9 %) in volleyball players. Meanwhile, the inter-limb asymmetries were reported to be very low for various variables associated with the leg press task in a study investigating male volleyball players (Mattes et al., 2018). The discrepancy of these results is suggesting that a single testing procedure is perhaps not sufficient to detect all aspects of imbalances in strength between the limbs.

A recent systematic review has suggested that inter-limb asymmetries may be related to impaired performance, but the results are not consistent across studies (Bishop et al., 2018). Namely, inter-limb asymmetries in lower body strength were associated with poorer jumping performance and output power during cycling, while weak associations or absence of associations have been shown between inter-limb asymmetries during jumping and sprinting performance and change-of-direction (CoD) ability (Bishop et al., 2018). Specifically, for volleyball players, Schons et al. (2019) reported that asymmetries in knee extensor isokinetic strength at 60 °/s could be related to poorer jumping performance ($r = -0.53$), however, their findings were not statistically significant. CoD ability was shown to be related to lower-limb strength (Tramel et al., 2019), however, no previous studies have investigated the relationships between inter-limb asymmetries and CoD

Received: 17 April 2020 / Accepted: 14 October 2020 / Published (online): 19 November 2020

performance.

Previous studies investigating the presence of inter-limb asymmetries or associations between inter-limb asymmetries and performance have mostly used only a few outcome measures within the same study, such as maximal torque or maximal force (Bishop et al., 2018). Other parameters of muscle capacity, such as rate of torque development (RTD) and particularly rate-of torque development scaling factor (RTD-SF), have been scarcely used so far. Moreover, studies focused on different muscle groups or tasks (jumps, single-leg strength tasks) to quantify inter-limb asymmetries and the associations with performance are inconsistent across athletes in general (Bishop et al., 2018) and specifically in volleyball (Cheung et al., 2012; Fort-Vanmeerhaeghe et al., 2016; Mattes et al., 2018; Schons et al., 2019). A comprehensive study is needed to assess the magnitude, agreement and relationships among inter-limb asymmetries in different tasks through different outcome measures. In line with the outlined paucity of evidence and differences between studies, the purpose of the present study was to explore a) the prevalence of strength and power lower body inter-limb asymmetries in volleyball players, b) the agreement between several different strength/power outcome measures (maximal isometric strength, RTD, RTD-SF, vertical jumping, jumping for distance and CoD tests) in terms of inter-limb asymmetry direction and magnitude, and c) the associations between inter-limb asymmetries and jumping and CoD performance.

Methods

Participants

For this study, 54 young volleyball players (25 males, 29 females; mean age: 17.8 ± 3.3 years; mean body height: 1.77 ± 0.11 m; mean body mass: 69.5 ± 12.9 kg) were recruited through two regional clubs. Inclusion criteria were: > 3 years of regular (> 3 times per week) volleyball training and age ≥ 15 years. Exclusion criteria were the presence of serious musculoskeletal injuries or pain syndromes at the time of testing or in the previous 6 months. The study protocol was approved by Slovenian National Medical Ethics Committee (approval number: 0120-99/2018/5) and conducted in accordance with the Helsinki declaration. Informed consents were obtained prior to the onset of the experiment. For underage participants, informed parental consents were obtained.

Study design, tasks and procedures

The present study was conducted as a single-visit cross-sectional investigation. The participants were required to complete the following unilateral tasks: a) single-leg vertical counter-movement (CMJ) jump on force plates, b) single-leg forward (SJ_{For}) and single-leg lateral jumps (SJ_{Lat}) for distance c) single-leg triple forward jumps (TJ_{For}) for distance, d) unilateral knee extension maximal isometric voluntary contraction (MVC) and rapid isometric pulses for RTD-SF calculation and e) two CoD tests, one requiring 90° turn (CoD_{90}) and the other requiring 180° turn(CoD_{180}). All tests were performed separately for each limb (or movement direction in case of CoD). The order of the tasks was random and counter-balanced across participants. The order of the limbs was randomized for each participant separately for each task.

Single leg CMJs (Figure 1C) were performed on force platforms (Quattro Jump, type 9290DD, Kistler, Winterthur, Switzerland). Participants were instructed to place their hands on the hip and to lift off the opposite leg by bending the knee to ~90° and wait for the examiner's que. They were instructed to lower themselves as quickly as possible and jump as high as possible. The depth of the counter-movement was instructed to be to the knee position of 90° which was visually controlled for. Familiarization trials (2-3 repetitions) were carried out for each participant. The technique of the jump as well as output force signals were monitored by the investigator. Special attention was given to the opposite leg, which was strictly forbidden to touch the force plate or to use its swing during the jump.

The remaining jump tasks (SJ_{For}, SJ_{Lat} and TJ_{For}) were performed on a flat surface (sport parquet). Detailed description of the procedures may be found elsewhere (Haitz et al., 2014; Meylan et al., 2009). In brief, measuring tapes were affixed to the ground and participants kept their hands on the hips. For SL_{For} (Figure 1 A) and SL_{Tri} (Figure 1D), the participants started with their toes aligned to the starting line. When ready, they were instructed to perform a single jump (SJ_{For}) or three consecutive jumps (TJ_{For}) for distance. The distance was recorded from the starting line to the point where the heel landed upon the completion of the jump (last jump in case of TJ_{For}). For the SJ_{Lat} (Figure 1B), the participants placed the medial border of the stance foot behind the starting line, with the other leg facing in the direction of the jump. Counter-movement was allowed and the participants landed on both limbs. The distance from the starting line to the medial border of the leg that executed the jump was recorded by the investigator. For all jumps, the average of the three repetitions was taken for further analysis for each leg for all of the jumps.

CoD_{90} and CoD_{180} were performed on a flat, non-slippery surface, as described before (Rouissi et al., 2016). To ensure accurate time measurements, we used a laser photo gate system (TCi Timing System, Brower Timing Systems, Draper, USA). For the CoD_{90}, the participants performed 5+5 m straight-line sprints, with a 90° turn in the middle. For CoD_{180}, the participants performed 5+5 m sprints with a 180° turn. For both tests, three repetitions were completed for each direction, and the best repetition was taken for further analyses. The turning point was marked with a cone for both tests. At all times, the participants started the test at their own will.

Knee extension maximal strength was evaluated on a custom-made dynamometer (S2P, Science to Practice, Ltd., Ljubljana, Slovenia) by performing the MVC task (Figure 1). The participants were instructed to contract as fast and as strong as possible (Maffiuletti et al., 2016), which enabled both maximal torque and rate of torque development (RTD) analysis. The participants were verbally encouraged to exert maximal effort for 3-5s. For each limb, the task was repeated three times, with 30-s rest periods in between. The best repetition for each limb was taken for further analysis. Additionally, we performed the assessment of the rate of torque development scaling factor

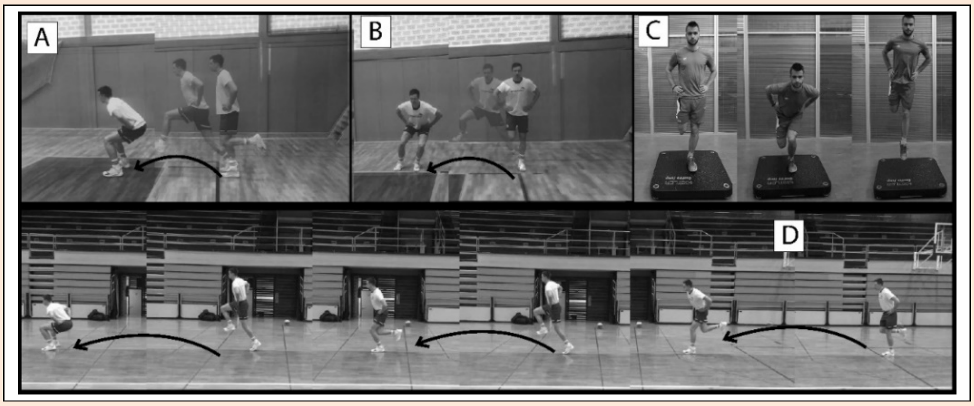

Figure 1. The jumping tests included single-leg forward jump (A), lateral single-leg jump (B), single-leg countermovement jump (C) and single-leg triple forward jump (D).

(RTD-SF), which is the slope of the relationships between the contraction intensity (torque) and RTD during rapid isometric pulses of varying intensities (Bellumori et al., 2011). For this purpose, the participants were instructed to produce quick bursts of contractions at four different intensities (20, 40, 60 and 80 % of maximal torque recorded during MVC). The order of the intensities was randomized between participants, but was kept the same within the participant for each leg. For each intensity, 25 trials were completed. Participants were provided with a computer screen that displayed continuous real-time feedback regarding the torque level, with a horizontal line placed at the desired intensity. Familiarization trials (5-10) were provided at each intensity to allow the participants to adjust the contraction intensity to the desired torque level. Participants were instructed to make sure that each individual contraction burst is as explosive as possible and to relax quickly.

Data processing and outcome measures

Data for SL_{For}, SL_{Lat}, SL_{Tri} CoD_{90}, and CoD_{180} was collected into pre-prepared printed spreadsheets and transcribed to MS Excel Software (Version 2016, Microsoft, Redmond, Washington, USA). Ground reaction force data from the force plates were sampled at 1000 Hz and low-pass filtered with Butterworth filter (10 Hz cut-off frequency, 2nd order). CMJ jump height (CMJ_H), average force (CMJ_F) and average power (CMJ_P) were automatically calculated from the force data in the acquisition software (MARS, Kistler, Winterthur, Switzerland). Knee extension torque data were sampled at 1000 Hz (ARS Software, S2P Ltd., Ljubljana, Slovenia) and low-pass filtered with Butterworth filter (20 Hz cut-off frequency, 2nd order). The maximal torque was determined as the maximal value during the 1-s interval of each repetition. RTD was calculated as the first derivative of the torque with respect to time and was assessed at 50 and 100 ms (RTD_{50} and RTD_{100}) after the contraction onset. Maximal RTD on the ascending part of the force-time curve was taken for computation of the RTD-SF, which was calculated as the slope of the linear regression line (peak RTD = RTD-SF *PeakTorque + Intercept) (Bellumori et al., 2011), using all data points from isometric pulses for each leg. The slope of this relationship ($RTD\text{-}SF_k$) was the primary outcome measure of interest. The other outcome measures were the R^2 coefficient, which is used to verify the linear relationship between peak torque and peak RTD. Before calculating the linear regression, each isometric pulse was visually inspected offline. Raw isometric pulses signals, as well as a scatter plot of the linear regression for a representative participant is presented in Figure 2. For all of the outcome measures, inter-limb asymmetry indexes were calculated, using the following equation:

$$Inter-limb\ asymmetry\ (\%) = \frac{Dominant - Nondominant}{Max\ (Dominant, Nondominant)}\ x\ 100\ \%$$

The dominant leg was defined as the ''leg you would use for single-leg jumps to achieve maximal jump height''.

Statistical analysis

Statistical analyses were performed in SPSS Statistical Software (Version 20., IBM, Armonk, USA) and MatLab (Version R2018a, Mathworks, Natick, USA). All data are presented as means ± standard deviations. For each of the outcome measures, the participants were assigned into two categories (symmetrical or asymmetrical, based on the >10 % threshold). The agreement between outcome variables regarding the categorization of the individuals was assessed by Cohen's Kappa (κ) coefficient, using a custom-made MatLab script (Mobahi, 2020). A similar analysis was also performed for categorization according to the direction (i.e. towards the self-reported dominant or non-dominant side). The agreement between the two outcomes was interpreted as slight (κ = 0.0 – 0.20), fair (κ = 0.21 – 0.40), moderate (κ = 0.41-0.60), substantial (κ = 0.61-0.80) and almost perfect (κ ≥ 0.81)(Sim and Wright, 2005). Additionally, the χ^2 test was performed to assess whether the frequency of asymmetries was different between the dominant and non-dominant side. Finally, we assessed the associations between asymmetries and performance measures (CMJ_H and CoD tests), and between all asymmetries themselves, with the Pearson correlation coefficient (0.0-0.1: no association; 0.1-0.4: weak association; 0.4-0.6: moderate association; 0.6-0.8: strong association; ≥ 0.8: very strong association) (Akoglu, 2018). For these

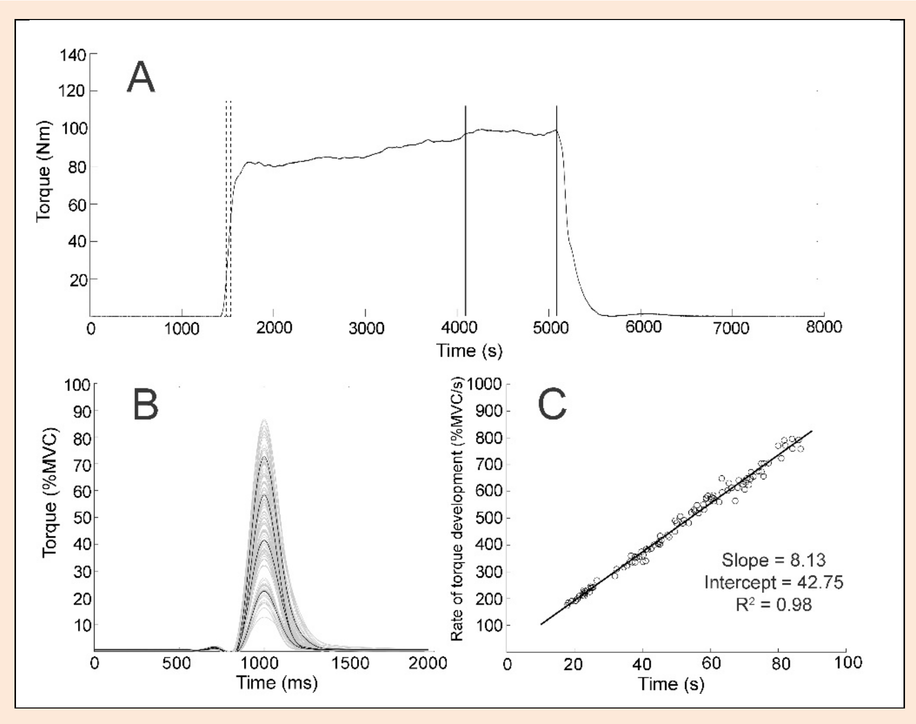

Figure 2. (A) An example of the torque signal during maximal voluntary contraction task, with the dashed line representing the time points at 50 and 100 ms after the onset of the torque rise. Maximal torque value during the 1-s interval (solid lines) was taken for further analyses. All rapid isometric pulses (B) for one dominant limb of one participant are shown, time-aligned to the onset of torque. The rate of torque development scaling factor calculation (C) results are also shown for the same participant.

analyses, the inter-limb asymmetry indexes were converted to absolute values (preserving the magnitude). For all analyses, the threshold for statistical significance was set to $p < 0.05$.

Results

Prevalence, magnitude and direction of asymmetries

Participants on average reported 4.4 ± 0.8 (range 4-8) training sessions per week, and to perform regular training for 7.3 ± 3.4 years (range 3-21). The mean values for all outcome measures for the dominant and non-dominant limb, as well as mean absolute asymmetry indexes, are presented in Table 1. The number of asymmetry indexes was evenly distributed between the non-dominant and dominant limb across participants for most outcome measures. The exceptions were SJ_{For} (66.7 % participants with superior dominant limb; $\chi^2 = 6.0$; $p = 0.014$), CMJ_H (66.7 % participants with superior dominant limb; $\chi^2 = 6.0$; $p = 0.014$) and CMJ_P (64.8 % participants with superior dominant limb; $\chi^2 = 4.7$; $p = 0.029$).

Based on the >10% inter-limb asymmetry threshold, we categorized each participant as symmetrical or asymmetrical. There were substantial differences among the outcome measures in terms of the percentage of participants that were categorized into each category. The results are summarized in Table 2. For both CoD tests, none of the participants were categorized as asymmetrical, therefore, the χ^2 test could not be computed.

Agreement between different outcome measures

The first set of analyses was calculated to assess the agreement between outcome measures in terms of categorization of participants according to the direction of the asymmetry (i.e. towards the self-reported dominant or non-dominant side). The agreement between outcome measures was poor in general (most $\kappa < 0.2$). The exceptions are the almost perfect agreement between all RTD_{50} and RTD_{100} ($\kappa = 0.86$; $p < 0.001$), substantial agreement between CMJ_P and CMJ_F ($\kappa = 0.73$; $p < 0.001$), moderate agreement between CMJ_H and CMJ_P ($\kappa = 0.48$; $p < 0.001$) and fair agreement between CMJ_H and CMJ_F ($\kappa = 0.40$; $p = 0.002$).

The second set of analyses was performed to assess the agreement between outcome measures in terms of categorization of participants to ''symmetrical'' or ''asymmetrical'', based on the 10 % threshold. As with the first categorization, the agreement between outcome measures was poor in general (most $\kappa < 0.2$). There was a substantial agreement between RFD_{50} and RFD_{100} ($\kappa = 0.63$; $p < 0.001$). No other agreements above $\kappa = 0.40$ were found.

Associations between inter-limb asymmetries obtained with different tests

Correlations coefficients between inter-limb asymmetry indexes, obtained with different tests and outcome measures are summarized in Table 3. All associations were very similar between genders. Most coefficients were small and statistically non-significant, with few exceptions. There was a very high correlation between asymmetries in RTD_{50} and RTD_{100} ($r = 0.96$). Moreover, moderate associations were shown between maximal knee torque and CMJ_F in males ($r = 0.41$), but not in females ($r = 0.29$). There was also a strong relationship between asymmetries in CMJ_H and CMJ_F in both genders (r = 0.83-0.89), moderate between CMJ_P and CMJ_F (r = 0.50-0.68), but there was no association between CMJ_P and CMJ_H (r = 0.20-0.33). Asymmetries in CMJ_H were also moderately related to asymmetries in SJ_{Lat} and TJ_{For} (r = 0.39-0.47).

Associations between inter-limb asymmetries and performance

Pearson correlation coefficients were computed between the arithmetic mean of the left and right leg outcome measures that are considered as measures of performance (CMJ_H and both CoD tests) and all inter-limb asymmetry indexes. CoD_{180} performance was weakly associated with asymmetry in CMJ_H (r = 0.29; p = 0.032) and asymmetry in RTD-SF_k (r = 0.30; p = 0.031). Since shorter times indicate better CoD_{180} performance, these correlations imply that more pronounced asymmetries were associated with worse performance. CoD_{90} performance was associated SJ_{Lat} (r = 0.31; p = 0.028). Since shorter times indicate better CoD_{90} performance, these correlations imply that asymmetries were associated with better performance. No additional associations were found when analyzing male participants alone, whereas for female participants, we found an additional moderate negative association between CMJ_H performance and asymmetry in CMJ_H (r = -0.42; p = 0.024).

Discussion

The aims of the present study were (a) to investigate the prevalence of lower body inter-limb strength and power asymmetries in volleyball players, (b) to assess the agreement between different strength/power outcome measures regarding the categorization of individuals in view of inter-limb asymmetry direction and magnitude and (c) to explore the associations between inter-limb asymmetries and performance. We found that the percentage of individuals that were classified as "asymmetrical" (based on the >10 % threshold) varies substantially among the outcome measures (e.g. 0 % for CoD tests and 68-75 % in RTD) and no clear tendency for one limb/side to be stronger/superior to the other for most outcome measures, with few exceptions (SJ_{For}, CMJ_H and CMJ_P), where the dominant limb was more often stronger.

Table 1. Summary of all outcome measures for both limbs and asymmetry indexes.

Outcome measure	Non-dominant limb (Mean ± SD)	Dominant limb (Mean ± SD)	Asymmetry index (%)
SJ_{Lat} [cm]	157.1 ± 25.8	159.3 ± 24	4.5 ± 5.1
TJ_{For}[cm]	537.3 ± 82.4	536.3 ± 86	4.3 ± 2.8
SJ_{For} [cm]	174.1 ± 22.6	177 ± 23	3.5 ± 3.2
CoD_{180} [s]	3.03 ± 0.17	3.03 ± 0.18	2.02 ± 1.83
CoD_{90} [s]	2.43 ± 0.23	2.44 ± 0.21	2.63 ± 1.97
Maximal knee torque [Nm/kg]	2.78 ± 8.64	2.97 ± 10	10.93 ± 8.52
RTD_{50} [%MVC/s]	512.6 ± 177.4	547.3 ± 191.1	26.3 ± 19.1
RTD_{100} [%MVC/s]	500.9 ± 136.7	513.4 ± 131.9	21.1 ± 15.5
CMJ_H [m]	0.14 ± 0.05	0.15 ± 0.05	10.24 ± 9.39
CMJ_P [W/kg]	16.2 ± 2.7	16.4 ± 2.6	6.5 ± 4.4
CMJ_F [N/kg]	15.7 ± 1.2	15.6 ± 1.2	3.6 ± 3
RFD-SF_{R2}	0.94 ± 0.04	0.94 ± 0.06	13.38 ± 11.08
RFD-SF_k	7.51 ± 1.28	7.07 ± 1.3	11.12 ± 9.67

SJ_{Lat} – single leg lateral jump for distance, TJ_{For} – single leg triple jump for distance, SJ_{For} – single-leg forward jump for distance; CoD – change-of-direction; MVC – maximal voluntary contrition; RTD – rate of torque development; CMJ – counter-movement jump; RTD-SF – rate of torque development scaling factor; SD – standard deviation.

Table 2. Categorization of participants into symmetrical or asymmetrical according to the threshold at 10% of asymmetry index.

	Above 10 % (n)	Below 10% (n)	Above 10% (%)	Below 10% (%)	χ^2	p-value
SJ_{Lat} [cm]	4	49	7.5	92.5	39.2	0.000
TJ_{For} [cm]	3	50	5.7	94.3	42.7	0.000
SJ_{For} [cm]	2	51	3.8	96.2	46.3	0.000
CoD_{180} [s]	0	53	0.0	100.0	/	/
CoD_{90} [s]	0	53	0.0	100.0	/	/
Maximal knee torque [Nm/kg]	27	27	50.0	50.0	1.0	1.000
RTD_{50} [%MVC/s]	41	13	75.9	24.1	14.5	0.000
RTD_{100} [%MVC/s]	37	17	68.5	31.5	7.4	0.006
CMJ_H [m]	20	33	37.7	62.3	3.6	0.057
CMJ_P [W/kg]	11	43	20.4	79.6	19.0	0.000
CMJ_F [N/kg]	2	51	3.8	96.2	46.3	0.000
RTD-SF_k	22	31	41.5	58.5	1.9	0.174

SJ_{Lat} – single leg lateral jump for distance, TJ_{For} – single leg triple jump for distance, SJ_{For} – single-leg forward jump for distance; CoD – change-of-direction; MVC – maximal voluntary contrition; RTD – rate of torque development; CMJ – counter-movement jump; RTD-SF – rate of torque development scaling factor.

Table 3. Person correlation coefficients among different asymmetry indexes.

	↓Correlations in males (left/lower section)						Correlations in females (right/upper section) →					
	SJ_{Lat}	TJ_{For}	SJ_{For}	CoD_{180}	CoD_{90}	$Knee_{MVC}$	RTD_{50}	RTD_{100}	CMJ_H	CMJ_P	CMJ_F	RTD-SF
SJ_{Lat}		0.251	0.305	0.094	-.452*	-0.002	-0.202	-0.201	.405*	-0.003	0.359	0.134
TJ_{For}	0.074		0.09	-0.248	-0.341	0.28	0.117	0.176	.397*	0.08	.387*	0.309
SJ_{For}	0.075	0.07		-0.075	-0.124	0.091	0.078	0.069	0.139	-0.003	0.16	-0.178
CoD_{180}	-0.296	-0.296	-0.366		0.249	-0.31	-0.332	-0.346	-0.081	0.037	-0.076	0.131
CoD_{90}	-0.052	-0.324	0.057	0.052		-0.225	-0.132	-0.155	-0.136	-0.008	-0.13	-0.109
$Knee_{MVC}$	-0.052	-0.059	0.38	-0.183	-0.049		0.364	.402*	.393*	0.04	0.292	-0.051
RTD_{50}	-0.046	-0.381	0.021	0.291	0.12	0.152		.965**	-0.087	-0.236	-0.198	-0.021
RTD_{100}	-0.038	-0.374	0.078	0.293	0.108	0.202	.960**		-0.036	-0.248	-0.129	-0.093
CMJ_H	.469*	.412*	0.286	-0.307	-0.29	0.228	-0.262	-0.12		0.204	.899**	0.054
CMJ_P	-0.028	-0.03	0.118	-0.128	0.08	0.37	0.082	0.251	0.328		.502**	0.204
CMJ_F	0.245	0.311	0.28	-0.233	-0.208	.413*	-0.129	0.04	.834**	.679**		0.018
RTD-SF	-0.064	-0.075	-0.208	-0.157	-0.083	-0.148	-0.378	-0.337	-0.079	-0.002	-0.004	

SJ_{Lat} – single leg lateral jump for distance, TJ_{For} – single leg triple jump for distance, SJ_{For} – single-leg forward jump for distance; CoD – change-of-direction; MVC – maximal voluntary contrition; RTD – rate of torque development; CMJ – counter-movement jump; RTD-SF – rate of torque development scaling factor.* $p < 0.05$; ** $p < 0.01$. Please note that upper/right portion of the table shows the correlations in females, while the left/lower portion shows the correlations in males.

The agreement among different outcome measures on whether the individual is "asymmetrical" and on the direction of the asymmetry was poor in general, with the exceptions of outcome measures within the same task (e.g. different RTD outcomes). Finally, both positive and negative associations between inter-limb asymmetries and performance outcome measures were found. In summary, this study challenges the common >10% asymmetry threshold by demonstrating that the magnitude and the direction of inter-limb asymmetries vary considerably between different outcome measures related to strength and power capacity. The second important novelty of the study is inclusion of the RTD-SF, a novel approach towards the assessment of muscular capacity that could represent an important addition to current assessment protocols.

Average inter-limb asymmetry indexes ranged from 2.1 to 26.3 %. Previous studies have reported high mean inter-limb asymmetry for CMJ_H (12.3 ± 9.5 %) (Fort-Vanmeerhaeghe et al., 2016), which is similar to our results (10.2 ± 9.4). The mean CMJ_H values were also very similar. Knee extensor strength asymmetries of volleyball players were previously tested in isokinetic conditions, and the mean values of the samples mostly fell within the range between 5 and 10 % (Cheung et al., 2012; Schons et al., 2019). In the present study, we found a mean asymmetry in isometric knee extension torque to be 10.9 ± 8.5 %, which is similar to what was recorded for slow, but not high isokinetic velocities (Cheung et al., 2012; Schons et al., 2019). Fort-Vanmeerhaeghe et al. (2016) also reported the number of participants with either stronger dominant (57 %) and non-dominant limb (43 %) in terms of CMJ_H results, which is similar to our results (67 % with stronger dominant limb). It seems that our results are generally in agreement with the data that has been collected before in volleyball players.

To the best of our knowledge, this is the first study that assessed the agreement between different strength/power tests regarding the classification of individual athletes as symmetrical or asymmetrical, or depending on the direction of the asymmetry. For the former, we used the >10% threshold, which is currently accepted as the value above which the difference between the limbs becomes meaningful (McGrath et al., 2016; Schiltz et al., 2009; Theoharopoulos and Tsitskaris, 2000). However, it appears that this threshold might not be appropriate for all outcome measures, and thus, the categorization of participants will not be uniform across outcome measures if the same threshold is used for all outcomes. Additionally, the agreement on the direction of the asymmetry was also poor among outcomes, suggesting that multiple assessment tasks should be performed during routine testing to obtain a comprehensive overview of individual's strength/power capabilities and inter-limb asymmetries. In terms of rehabilitation outcomes, some authors have advocated that a lower threshold such as 5 % should be used (McGrath et al., 2016). On the other hand, it has been suggested 10 % threshold is too low to expect a serious detrimental impact on performance (Lockie et al., 2014; Yoshioka et al., 2010). Clearly, further research is needed to determine the appropriate clinically meaningful thresholds.

Another novelty of the study is the inclusion of RTD-SF (Bellumori et al., 2011), which has not been studied before in volleyball players. The mean values for $RDT\text{-}SF_k$ we obtained (7.1 – 7.5) were similar to those recorded in previous studies that investigated knee extensors (Bellumori et al., 2011; Boccia et al., 2018; Djordjevic and Uygur, 2018). To the best of the authors' knowledge, there are no studies published that examined the inter-limb asymmetries in $RTD\text{-}SF_k$. According to the >10 % threshold, 58.5 % of the participants had symmetrical values for $RTD\text{-}SF_k$. The inter-limb asymmetries in $RTD\text{-}SF_k$ were moderately associated with CoD_{180} performance time. Although further investigation is needed to confirm this, the inter-limb symmetry in $RTD\text{-}SF_k$ could represent an important performance-determining factor. We encourage future investigators to include RFD-/RTD-SF measurements in their experimental protocols. Previous studies have already shown high sensitivity of $RTD\text{-}SF_k$ to ageing (Bellumori et al., 2013) and motor impairments (Uygur et al., 2020). More studies are needed to elucidate whether $RTD\text{-}SF_k$ could be useful in strength and conditioning, as well as rehabilitation research and routine testing.

CoD performance time was also negatively associated with the magnitude of the CMJ_H inter-limb asymmetry. Previous studies have demonstrated positive relationships between CMJ_H and CoD performance

(Barnes et al., 2007), however, the present study was the first to show that inter-limb asymmetries in CMJ_H are linked with lower CoD performance. Inter-limb asymmetries in CMJ_H were also associated with the performance in the same task, but only in female participants. The remaining associations that we have found indicated that larger inter-asymmetries contributed to better performance. Such a phenomenon has been reported before for the cycling task (Bini and Hume, 2015), however, other studies to date have reported either negative associations or no association between inter-limb asymmetries and performance (Bishop et al., 2018). The positive associations that we have obtained corroborate our previous statement that multiple tests should be performed for obtaining a comprehensive picture of the athlete's status. Subsequent research should further explore the association between inter-limb asymmetries of various outcome measures and athletic performance.

Correlations among different asymmetry indexes were generally low. Exceptions include high correlations between RTD_{50} and RTD_{100}, and between CMJ_H and CMJ_F. The frist association implies that one RTD measure could be sufficient to detect the asymmetries in explosive strength. The second correlation highlights that asymmetries in jumping performance (jump height) and underlying mechanics (force) are related, which means that field-based measurements of jump height can be used to comprehensively assess inter-limb asymmetries, when instrumented measurement methods (e.g., force plates) are not available.

Conclusion

This study showed that the different lower-limb strength and power tests may produce substantially different results in view of inter-limb asymmetry indexes and associations with performance. Routine testing in young volleyball players should include the assessment of both simple single-joint, as well as multi-joint strength/power tests. We advise the practitioners caution when referring to inter-limb asymmetry cut-off values (expl. 10%) as the threshold above which the inter-limb asymmetries become detrimental. The results of this study can serve as guidance regarding the expected values and ranges of inter-limb asymmetries in different strength/power outcomes, in order to consider intervening when the detected values for a given athlete exceed this range. For example, this study found that inter-limb asymmetry in CMJ_H was associated with poorer performance in CoD tasks. Since CMJ_H inter-limb asymmetries ranged from 0.5-20 %, which is in accordance to previous investigations (Fort-Vanmeerhaeghe et al., 2016), it would be reasonable to reasonable to try to reduce these asymmetries below 10%. On the other hand, the mean inter- asymmetries in CoD tasks and hops for distance were much lower (2-4 %), and a value of 10 % could already represent a red flag in view of these variables.

Acknowledgements

The authors would like to thank mr. Jernej Pleša for helping with participant recruitment and data acquisition. The study was supported by the Slovenian Research Agency through the programme 'Kinesiology of monostructural, polystructural and conventional sports' [P5-0147 (B)] and the project TELASI-PREVENT [L5-1845] (Body asymmetries as a risk factor in musculoskeletal injury development: studying aetiological mechanisms and designing corrective interventions for primary and tertiary preventive care). The authors have no conflicts of interests to declare. The experiments comply with the current laws of the country in which they were performed.

References

Akoglu, H. (2018) User's guide to correlation coefficients. *Turkish Journal of Emergency Medicine* **18**, 91-93.

Barnes, J.L., Schilling, B.K., Falvo, M.J., Weiss, L.W., Creasy, A.K., Fry, A.C. (2007) Relationship of jumping and agility performance in female volleyball athletes. *Journal of Strength and Conditioning Research* **21**, 1192–1196.

Baugh, C.M., Weintraub, G.S., Gregory, A.J., Djoko, A., Dompier, T.P., Kerr, Z.Y. (2018) Descriptive Epidemiology of Injuries Sustained in National Collegiate Athletic Association Men's and Women's Volleyball, 2013-2014 to 2014-2015. *Sports Health* **10**, 60–69.

Bellumori, M., Jaric, S., Knight, C.A. (2013) Age-related decline in the rate of force development scaling factor. *Motor Control* **17**, 370–381.

Bellumori, M., Jaric, S., Knight, C.A. (2011) The rate of force development scaling factor (RFD-SF): Protocol, reliability, and muscle comparisons. *Experimental Brain Reserach* **212**, 359–369.

Bini, R.R., Hume, P.A. (2015). Relationship between pedal force asymmetry and performance in cycling time trial. *J Sports Med Phys Fitness* **55**, 892–898.

Bishop, C., Turner, A., Read, P. (2018) Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *Journal of Sports Sciences* **36**, 1135–1144.

Boccia, G., Dardanello, D., Brustio, P.R., Tarperi, C., Festa, L., Zoppirolli, C., Pellegrini, B., Schena, F., Rainoldi, A. (2018) Neuromuscular fatigue does not impair the rate of force development in ballistic contractions of submaximal amplitudes. *Frontiers in Physiology* **9**, 1503.

Cheung, R., Smith, A., Wong, D. (2012) H:Q ratios and bilateral leg strength in college field and court sports players. *Journal of Human Kinetics* **33**, 63–71.

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. *American Journal of Sports Medicine* **36**, 1469–1475.

Djordjevic, D., Uygur, M. (2018) Methodological considerations in the calculation of the rate of force development scaling factor. *Physiological Measurement* **39**, 015001.

Fort-Vanmeerhaeghe, A., Gual, G., Romero-Rodriguez, D., Unnitha, V. (2016) Lower Limb Neuromuscular Asymmetry in Volleyball and Basketball Players. *Journal of Human Kinetics* **50**, 135–143.

Hadzic, V., Sattler, T., Veselko, M., Markovic, G., Dervisevic, E., 2014. Strength asymmetry of the shoulders in elite volleyball players. *Journal of Athletic Training* **49**, 338–344.

Haitz, K., Shultz, R., Hodgins, M., Matheson, G.O. (2014) Test-retest and interrater reliability of the functional lower extremity evaluation. *Journal of Orthopaedic & Sports Physical Therapy* **44**, 947–954.

Keller, R.A., De Giacomo, A.F., Neumann, J.A., Limpisvasti, O., Tibone, J.E. (2018) Glenohumeral Internal Rotation Deficit and Risk of Upper Extremity Injury in Overhead Athletes: A Meta-Analysis and Systematic Review. *Sports Health* **10**, 125–132.

Kilic, O., Maas, M., Verhagen, E., Zwerver, J., Gouttebarge, V. (2017) Incidence, aetiology and prevention of musculoskeletal injuries in volleyball: A systematic review of the literature. *European Journal of Sport Science* **17**, 765-793

Lockie, R.G., Callaghan, S.J., Berry, S.P., Cooke, E.R.A., Jordan, C.A., Luczo, T.M., Jeffriess, M.D. (2014) Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. *Journal of Strength and Conditioning Research* **28**, 3557–66.

Maffiuletti, N.A., Aagaard, P., Blazevich, A.J., Folland, J., Tillin, N., Duchateau, J. (2016) Rate of force development: physiological and methodological considerations. *European Journal of Applied Physiology* **116**, 1091-116

Mattes, K., Wollesen, B., Manzer, S. (2018) Asymmetries of maximum trunk, hand, and leg strength in comparison to volleyball and fitness athletes. *Journal of Strength and Conditioning Research* **32**, 57–65.

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**, 289–302.

Meylan, C., McMaster, T., Cronin, J., Mohammad, N.I., Rogers, C., Deklerk, M. (2009) Single-leg lateral, horizontal, and vertical jump assessment: Reliability, interrelationships, and ability to predict sprint and change-of-direction performance. *Journal of Strength and Conditioning Research s* **23**, 1140–1147.

Mobahi, H. (2020) Computing Kappa Index. Available from URL: https://www.mathworks.com/matlabcentral/fileexchange/22645-computing-kappa-index [acessed: 8 February 2020]

Mokha, M., Sprague, P.A., Gatens, D.R. (2016) Predicting musculoskeletal injury in national collegiate athletic association division II athletes from asymmetries and individual-Test versus composite functional movement screen scores. *Journal of Athletic Training* **51**, 276–282.

Myer, G.D., Jayanthi, N., Difiori, J.P., Faigenbaum, A.D., Kiefer, A.W., Logerstedt, D., Micheli, L.J. (2015) Sport Specialization, Part I: Does Early Sports Specialization Increase Negative Outcomes and Reduce the Opportunity for Success in Young Athletes? *Sports Health* **7**, 437–442.

Pollard, K.A., Shields, B.J., Smith, G.A. (2011) Pediatric volleyball-related injuries treated in US emergency departments, 1990-2009. *Clinical Pediatrics (Philadelphia)* **50**, 844–852.

Rouissi, M., Chtara, M., Owen, A., Chaalali, A., Chaouachi, A., Gabbett, T., Chamari, K. (2016) Effect of leg dominance on change of direction ability amongst young elite soccer players. *Journal of Sports Sciences* **34**, 542–548.

Schiltz, M., Lehance, C., Maquet, D., Bury, T., Crielaard, J.M., Croisier, J.L. (2009) Explosive strength imbalances in professional basketball players. *Journal of Athletic Training* **44**, 39–47.

Schons, P., Da Rosa, R.G., Fischer, G., Berriel, G.P., Fritsch, C.G., Nakamura, F.Y., Baroni, B.M., Peyré-Tartaruga, L.A. (2019) The relationship between strength asymmetries and jumping performance in professional volleyball players. *Sport Biomechanics* **18**, 515–526.

Seminati, E., Minetti, A.E. (2013) Overuse in volleyball training/practice: A review on shoulder and spine-related injuries. *European Journal of Sport Science* **13**, 732-43.

Sim, J., Wright, C.C. (2005) The Kappa Statistic in Reliability Studies: Use, Interpretation, and Sample Size Requirements. *Physical Therapy* **85**, 257–268.

Theoharopoulos, A., Tsitskaris, G. (2000) Isokinetic evaluation of the ankle plantar and dorsiflexion strength to determine the dominant limb in basketball players. *Isokinetics and Exercise Science* **8**, 181–186.

Tramel, W., Lockie, R.G., Lindsay, K.G., Dawes, J.J. (2019) Associations between Absolute and Relative Lower Body Strength to Measures of Power and Change of Direction Speed in Division II Female Volleyball Players. *Sport (Basel, Switzerland)* **7**, 160.

Uygur, M., de Freitas, P.B., Barone, D.A. (2020) Rate of force development and relaxation scaling factors are highly sensitive to detect upper extremity motor impairments in multiple sclerosis. *J Neurol Sci* **408**, 116500.

Yoshioka, S., Nagano, A., Hay, D.C., Fukashiro, S., (2010) The effect of bilateral asymmetry of muscle strength on jumping height of the countermovement jump: A computer simulation study. *Journal of Sports Sciences* **28**, 209–218.

Key points

- Different lower-limb strength and power tests may produce substantially different results in view of inter-limb asymmetry indexes and associations with performance in volleyball players.
- Practitioners are advised to be cautious when referring to inter-limb asymmetry cut-off values (e.g. 10%) as the threshold above which the inter-limb asymmetries become detrimental.
- The association between inter-limb asymmetries of various outcome measures and athletic performance is still poorly understood.

AUTHOR BIOGRAPHY

Žiga KOZINC

Employment

Andrej Marusic Institute and Faculty of Health Sciences, University of Primorska, Koper, Slovenia.

Degree

MSc

Research interests

Physical conditioning and musculoskeletal injury prevention and rehabilitation, ergonomics.

E-mail: ziga.kozinc@iam.upr.si

Nejc ŠARABON

Employment

University of Primorska, Faculty of Health Sciences, Koper, Slovenia and S2P, Science to Practice, Ltd., Ljubljana, Slovenia.

Degree

PhD

Research interests

Motor control and behaviour, physical conditioning and musculoskeletal injury prevention and rehabilitation, ergonomics, sport science technology.

E-mail: nejc.sarabon@fvz.upr.si

✉ **Prof. Dr. Nejc Šarabon**

University of Primorska, Faculty of Health Sciences, Polje 42, SI-6310 Izola, Slovenia