INTERLIMB ASYMMETRIES IN GROUND REACTION FORCE TIME-SERIES DURING BI-LATERAL COUNTERMOVEMENT JUMPS

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Principal component analysis (PCA) of waveforms can provide useful information about biomechanical patterns throughout a movement. The purposes of this study were to 1) use PCA to identify interlimb asymmetries in the ground reaction force (GRF) time-series data of the left and right leg during a bi-lateral countermovement jump (CMJ) and 2) determine if asymmetries in GRF time-series were associated with CMJ performance. Eight female collegiate soccer players performed three maximal effort CMJ. PCA extracted five principal components (PC) scores, eigenvalues, and eigenvectors from the GRF data. PC2 scores differed significantly between two legs, but only PC3 scores were positively correlated with CMJ height. Future research should investigate whether identified asymmetries in GRF time-series data are associated with sport performance or injury risk.

KEYWORDS: sports, biomechanics, vertical jump, principal components analysis

INTRODUCTION: Interlimb asymmetry is prevalent in athletes since a variety of sports require repeated unilateral or dominant side performance during tasks such as kicking, shooting, or sprinting (Bailey et al., 2013; Bishop et al., 2021; Bishop et al., 2017; Bishop et al., 2018a; Hart et al., 2014; Raya-González et al., 2020). Recent works suggest that interlimb asymmetry could be a potential risk factor for sports injuries and limit performance (Bailey et al., 2013; Bishop et al., 2018a; Impellizzeri et al., 2007). Thus, strength and conditioning coaches and athletic trainers often monitor athletes' limb symmetry during training (Bishop et al., 2020; Bishop et al., 2018b). Some practitioners also assess and monitor interlimb asymmetry in injured athletes during rehabilitation to guide for return-to play decisions (Paterno et al., 2007; Rohman et al., 2015).

Previous research has investigated the influence of interlimb asymmetry on performance, but whether unequal performance of two limbs is detrimental to sports performance is not clear (Bailey et al., 2013; Bishop et al., 2018a; Hart et al., 2014; Loturco et al., 2019; Raya-González et al., 2020). Some studies reported that greater asymmetry was associated with worse performance of sports activities such as jump height or kicking accuracy (Bailey et al., 2013; Bell et al., 2014; Hart et al., 2014). On the other hand, other researchers did not find associations between asymmetry and performance (Loturco et al., 2019; Raya-González et al., 2020). For example, even elite athletes may still exhibit large interlimb asymmetries without deleterious effects on their neuromuscular system's ability to perform at high levels and not get hurt (Loturco et al., 2019).

To date, many studies calculate interlimb asymmetries from discrete variables such as peak force during bilateral tasks, such as the countermovement jump (CMJ). However, these discrete variables can lead to a loss of information about the original time-series data and might not be sensitive to detect certain features relevant to task performance (Deluzio et al., 2014). Compared to the discrete analysis, times-series analysis such as principal component analysis (PCA) can identify features and variations within waveforms across time and help differentiate between groups or conditions (Deluzio & Astephen, 2007).Time-series analysis of

CMJ can provide more detailed information about an athlete's neuromuscular function and jumping strategy throughout the entire jump (Floría et al., 2016; Floría et al., 2019). Thus, the use of PCA of waveforms may also provide a better method for identifying athletes with interlimb asymmetry, which could then be used to inform training program to improve sports-specific performance (e.g., kicking) or avoid injuries (e.g., ACL). Therefore, the primary aim of this study was to identify interlimb asymmetry in the ground reaction force (GRF) time-series data via PCA. A secondary aim was to determine if asymmetries in GRF time-series were associated with CMJ performance.

METHODS: Eight NCAA Division I female soccer players (height: 1.77 ± 0.03 m; and body mass: 66.8 ± 7.1 kg) were recruited for this study. All players were familiar with CMJ test procedures. The study was approved by the local University's Institutional Review Board and all players provided written informed consent.

Before CMJ testing, each player performed a standardized warm-up that includes simple callisthenic exercises and several submaximal and maximal jumping tasks. Participants then performed three maximal effort CMJs with at least 30 seconds rest between jumps. Athletes were instructed to place their hands on their hip, lower down to their preferred depth, and jump as high as possible for all CMJ trials.

Ground reaction force (GRF) data during the CMJ were recorded with two in-ground force plates (AMTI) at 1000 Hz. GRF data were filtered with a fourth-order low-pass Butterworth filter at a cut-off frequency of 50 Hz (Harry et al., 2020). Left and right GRF data were analysed across the entire movement phase, which was defined from the unweighing to the flight phase based on the vertical GRF. The unweighing phase began when the GRF fell below 95% of body weight (Meylan et al., 2011). The beginning of the flight phase was defined when GRF is reduced below 10N (Pérez-Castilla et al., 2021). All data were normalized to 101 points with cubic spline interpolation. CMJ height was calculated with the take-off velocity method (CMJ height = $v^2/2g$, v = velocity, g = gravitational acceleration).

All PCA and statistical analyses were performed in Python 3.8 (Enthought, Inc., Austin, TX, USA, Austin, TX, USA). Briefly, time-series data were combined into a matrix that contained three CMJ trials of each player's right and left GRF (44 [1-3 trials x 2 legs x 8 participants] x 101 [time normalized data points]). Two trials from two players were discarded due to technical problems. The matrix (44x101) was centred to the mean of each time point (i.e., column). The PCA was used to extract and calculate principal component (PC) scores, eigenvalues, eigenvectors, and variance components from the GRF data (Figure 1).

Normality for PC score distributions were tested with the Shapiro–Wilk test. Paired t-tests were used to compare right and left PC scores for each extracted PC. Pearson correlation coefficients were calculated to determine the association between PC scores and CMJ height. The statistical significance was set to an α-level of 0.05.

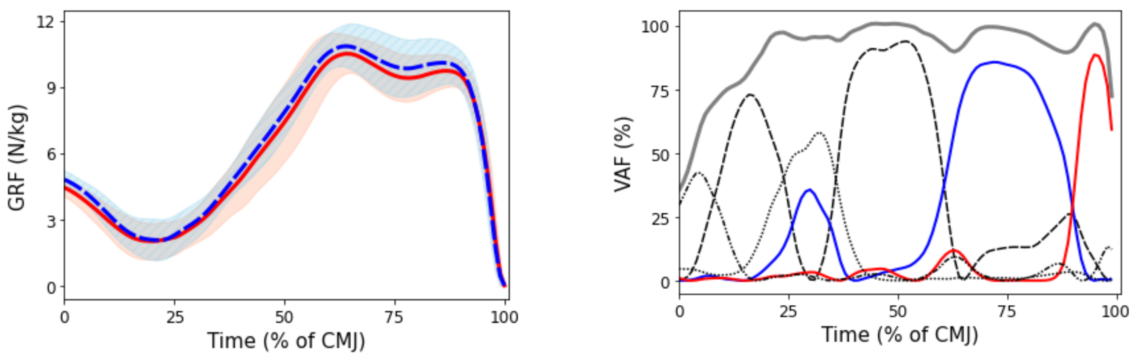

Figure 1: Ensemble average (mean±SD) for body-mass normalized left (red line) and right (dashed blue line) ground reaction force (GRF) time-series data during CMJ (left). Variance accounted for (VAF) of the GRF time-series data by the principal components (right). Total VAF (grey), VAF by PC1 (black dashed), PC2 (blue), PC3 (red), PC4 (black dotted), PC5 (black dash-dotted).

RESULTS: Five PC were extracted and explained 90% of the total variation in GRF time-series data (Figure 1 left). The five PC explained 43.9, 27.7, 10.7, 6.9, and 3.6%, respectively (Figure 1 right). The PC scores of the second PC (PC2) differed significantly between the left (-1.11±4.75) and the right (1.11±5.97) leg (p = 0.028). However, only the PC scores of the third PC (PC3) were positively correlated with CMJ height (r = 0.675, p = 0.001).
To understand the each effects of the PC, the ensemble average GRF data were represented with +/- deviations by multiplying the eigenvectors with one and a half standard deviation of the corresponding PC scores (O'Connor & Bottum, 2009) (Figure 2).

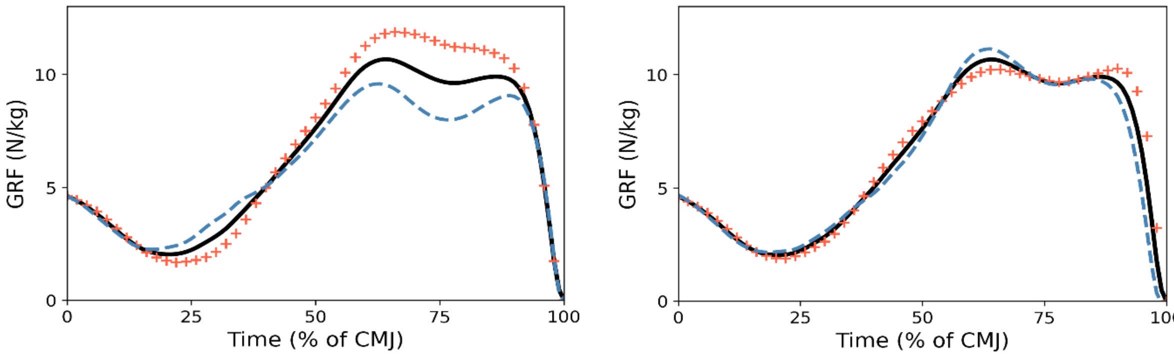

Figure 2: Ensemble average (black line) of body-mass normalized ground reaction force (GRF) time-series data during the CMJ along with the different effects of PC2 (left) or PC3 (right) on the shape of the GRF curves (effects of positive and negative PC scores are demonstrated with +/- symbols, respectively).

DISCUSSION: The purpose of our study was to use PCA to identify interlimb asymmetries in the left and right GRF time-series data and investigate if asymmetries were associated with CMJ performance. The main finding showed significant asymmetry in the scores of PC2, which captured variation in the amplitude of GRF time-series data during 20-40% (~unweighing) and 60-85% (~early propulsion) of the CMJ. Positive PC scores were associated with greater eccentric GRF during unweighing phase and greater concentric GRF during early propulsion phase. Therefore, athletes produced more eccentric and concentric force with their right leg than left leg during unweighing and early propulsion phase. Previous research quantified interlimb asymmetries with discrete variables such as peak GRF during CMJ (Bell et al., 2014; Newton et al., 2006).
Although the PCA approach revealed interlimb difference in GRF time-series data, the scores for this specific PC were not associated with CMJ height. This finding is contrary to other studies that reported that discrete GRF asymmetry values during unweighing and propulsion phase were associated with CMJ performance (Bailey et al., 2013; Bell et al., 2014). In the current study only the scores for PC3 were associated with CMJ height (Figure 2 right), but these scores did not differ between the left and right leg. PC3 explained variation in the GRF time-series data during 85-100% (~late propulsion to take-off) of the CMJ. This finding is similar to previous discrete analyses that showed athletes with better jumping ability also applied greater force during the latter part of propulsion phase (Floría et al., 2016; González-Badillo & Marques, 2010). Collectively, the results of our study suggest that investigating asymmetries via PCA of waveforms can provide insight into interlimb asymmetries within specific movement phases. Such information could help identify athletes with interlimb asymmetry and inform training efforts to prevent improve performance or decrease injury risk.
CONCLUSION: The current study used PCA to investigate interlimb asymmetries in GRF time-series data and showed that while GRF time-series data exhibited some right and left force production asymmetries during the unweighing and early propulsion phases, these asymmetries were not detrimental to CMJ height. Future research should use PCA to investigate asymmetries in time-series data to determine whether the identified asymmetries are associated with sport performance or injury risk.

REFERENCES

Bailey, C., Sato, K., Alexander, R., et al. (2013). Isometric force production symmetry and jumping performance in collegiate athletes. *Journal of Trainology, 2*(1), 1-5.
Bell, D. R., Sanfilippo, J. L., Binkley, N., et al. (2014). Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *J Strength Cond Res, 28*(4), 884.
Bishop, C., Read, P., McCubbine, J., et al. (2021). Vertical and horizontal asymmetries are related to slower sprinting and jump performance in elite youth female soccer players. *J Strength Cond Res, 35*(1), 56-63.
Bishop, C., Turner, A., Jarvis, P., et al. (2017). Considerations for selecting field-based strength and power fitness tests to measure asymmetries. *J Strength Cond Res, 31*(9), 2635-2644.
Bishop, C., Turner, A., & Read, P. (2018a). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *J Sports Sci, 36*(10), 1135-1144.
Bishop, C., Turner, A., & Read, P. (2018b). Training methods and considerations for practitioners to reduce interlimb asymmetries. *Strength & Conditioning Journal, 40*(2), 40-46.
Deluzio, K., & Astephen, J. (2007). Biomechanical features of gait waveform data associated with knee osteoarthritis: an application of principal component analysis. *Gait & posture, 25*(1), 86-93.
Deluzio, K. J., Harrison, A. J., Coffey, N., et al. (2014). The analysis of biomechanical waveform data. In D. G. E. Robertson, G. E. Caldwell, J. Hamill, G. Kamen, & S. N. Whittlesey (Eds.), Research methods in biomechanics (2nd ed., pp. 317–337). Champaign, IL: Human Kinetics.
Floría, P., Gómez-Landero, L. A., Suárez-Arrones, L., et al. (2016). Kinetic and kinematic analysis for assessing the differences in countermovement jump performance in rugby players. *J Strength Cond Res, 30*(9), 2533-2539.
Floría, P., Sánchez-Sixto, A., & Harrison, A. J. (2019). Application of the principal component waveform analysis to identify improvements in vertical jump performance. *J Sports Sci, 37*(4), 370-377.
González-Badillo, J. J., & Marques, M. C. (2010). Relationship between kinematic factors and countermovement jump height in trained track and field athletes. *J Strength Cond Res, 24*(12), 3443-3447.
Harry, J. R., Blinch, J., Barker, L. A., et al. (2020). Low-Pass Filter Effects on Metrics of Countermovement Vertical Jump Performance. *J Strength Cond Res*.
Hart, N. H., Nimphius, S., Spiteri, T., et al. (2014). Leg strength and lean mass symmetry influences kicking performance in Australian Football. *Journal of sports science & medicine, 13*(1), 157.
Impellizzeri, F. M., Rampinini, E., Maffiuletti, N., et al. (2007). A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Medicine & Science in Sports & Exercise, 39*(11), 2044-2050.
Loturco, I., Pereira, L. A., Kobal, R., et al. (2019). Do asymmetry scores influence speed and power performance in elite female soccer players? *Biology of sport, 36*(3), 209.
Meylan, C. M., Nosaka, K., Green, J., et al. (2011). The effect of three different start thresholds on the kinematics and kinetics of a countermovement jump. *J Strength Cond Res, 25*(4), 1164-1167.
Newton, R. U., Gerber, A., Nimphius, S., et al. (2006). Determination of functional strength imbalance of the lower extremities. *J Strength Cond Res, 20*(4), 971-977.
O'Connor, K. M., & Bottum, M. C. (2009). Differences in cutting knee mechanics based on principal components analysis. *Med Sci Sports Exerc, 41*(4), 867-878.
Pérez-Castilla, A., Fernandes, J. F., Rojas, F. J., et al. (2021). Reliability and Magnitude of Countermovement Jump Performance Variables: Influence of the Take-off Threshold. *Meas Phys Educ Exerc Sci*, 1-9.
Raya-González, J., Bishop, C., Gómez-Piqueras, P., et al. (2020). Strength, jumping, and change of direction speed asymmetries are not associated with athletic performance in elite academy soccer players. *Frontiers in psychology, 11*, 175.
Rohman, E., Steubs, J. T., & Tompkins, M. (2015). Changes in involved and uninvolved limb function during rehabilitation after anterior cruciate ligament reconstruction: implications for Limb Symmetry Index measures. *Am J Sports Med, 43*(6), 1391-1398.