



OPEN

Dynamic balance and explosive strength appears to better explain single leg hop test results among young elite female basketball athletes

Fernando Dominguez-Navarro^{1,2}, Jose Casaña^{1✉}, Borja Perez-Dominguez¹, Borja Ricart-Luna³, Pedro Cotolí-Suárez³ & Joaquin Calatayud¹

To analyze the impact of balance, lower-limb explosive strength and anthropometric variables on the result of the hop test in young elite female basketball athletes. Ninety young elite female basketball athletes (13–17 years), without current or recent lower-limb injury, were assessed in the off-season period of July 2021. Single leg hop test, countermovement jump, Y balance test and anthropometric outcomes were assessed. A correlation study and a regression model were performed to investigate the influence of such outcomes and the value of their participation on the hop test results. It was found a low-to-moderate correlation effect size for both countermovement jump (distance and power flight) and Y balance test values (except interlimb outcomes) with the single leg hop test results. Anthropometric outcomes did not show significant correlation ($p > 0.05$). Regression model revealed that for right hop test, countermovement jump values exhibited an adjusted determination coefficient of 0.408, ($\beta = 0.249$, $p = 0.013$), For left hop test, again the countermovement jump values ($\beta = 0.229$, $p = 0.025$), and left Y balance test values ($\beta = 0.331$, $p = 0.011$) jointly obtained an adjusted determination coefficient of 0.263 significant predictive value for countermovement jump outcomes in both right ($\beta = 0.249$, $p = 0.013$; $\beta = 0.301$; $p = 0.031$) and left leg ($\beta = 0.229$, $p = 0.025$; $\beta = 0.365$, $p = 0.040$), as well as certain Y balance outcomes values. Explosive strength, and dynamic balance although to a lesser extent, appear to be the most relevant physical-functional factors influencing the single leg hop test results among young elite female basketball athletes. These findings may serve as a basis to implement targeted interventions, such as plyometric and balance training, for an enhancement on functional rehabilitation and reducing the risk of injury related to the hop test results.

The practice of sports carries an intrinsic risk of suffering sport injuries, knowing that this risk, due to neuromuscular, biomechanical and hormonal reasons, is greater in female athletes^{1,2}. In female basketball, lower-limb injuries are the most prevalent, with an increase in the number of cases reported during the last decade³. This situation entails negative aspects for the athlete on a physical and psychological level⁴, whereas the issue becomes even more important in young athletes, as the injury could interfere with their physical and professional development⁵.

Detecting athletes at higher risk of injury is the first step in the injury prevention process. The assessment of the physical-functional status becomes crucial for this objective, serving both as a starting point for designing a conditioning injury prevention program and to monitor recovery⁶. Indeed, the hop test is a widely used tool to assess the functional capacity of the lower limb, requesting a propulsive action to perform a horizontal jump and landing⁷. Its results have a functional implication, since they are useful in predicting the risk of lower limb injuries⁸, detecting functional improvements⁹, and guiding return-to sport decisions¹⁰. The study of

¹Exercise Intervention for Health Research Group (EXINH-RG), Department of Physiotherapy, University of Valencia, Calle Gascó Oliag 5, 46010 Valencia, Spain. ²Department of Physiotherapy, Faculty of Health Sciences, European University of Valencia, Valencia, Spain. ³I+D+I Alqueria LAB Department, Valencia Basket Club, Valencia, Spain. ✉email: jose.casana@uv.es

its psychometric properties has demonstrated that it is a valid and reliable tool for functional assessment^{11,12}, which has led to its recommended use in the field of sports in the context of both prevention and recovery from injuries⁷.

As a functional test, the hop test has a global approach where different systems and physical capacities will be required and integrated for its performance. Deficiencies in the neuromuscular and biomechanical systems may lead to abnormal hop patterns, which requires a segmented study of these factors to better elucidate interpretation of hop test results.

High muscle strength is one of the most studied influential factors. Specifically, peak knee flexors and extensors torque and rate of torque development are shown to positively correlate to hop distance outcomes^{13–15}. Discussed issues of this assessment include that the force produced is in an open kinetic chain, unlike most sporting activities; and that the joint angulation in the measurement influences the results¹³. Instead of an analytic evaluation, the measurement of lower limb explosive strength, evaluated with maneuvers such as the vertical jump, has been proposed as an alternative for its analysis, with studies revealing a positive correlation between the vertical and longitudinal jump distances achieved¹⁶. However, muscular strength alone does not seem to account for the dynamic stability necessary to hop effectively¹⁷, so dynamic balance is also required. Dynamic balance can be understood as the ability to keep the center of gravity stable in situations of movement, such as hop distance. Previous research indicates that diminished ability for dynamic balance induces altered hop patterns¹⁸. In addition, the biomechanics of this movement are also influenced by the anthropometric characteristics of the athlete. Different levels of BMI and leg length appear to vary the lever arms and moments exerted on the lower extremities during jumping¹⁹. Furthermore, it is not entirely clear how these factors specifically influence female basketball athletes, as these characteristics have been found to differ from those of athletes of the same age who practice other sports²⁰.

Considering the hop test as a global movement, which involves the state and functioning of different neuromuscular and biomechanical aspects, little is known about the degree of participation of each of these elements and their ultimate implication on the test results. Therefore, it is relevant to study the impact of these physical capacities on its execution for a better understanding of its functional composition. The aim of this research is to analyze the impact of dynamic balance, lower-limb explosive strength and anthropometric outcomes on the result of the hop test in young elite female basketball athletes. We hypothesized that these physical-functional capacities, as well as leg length, will contribute to the results on the hop test.

Methods

Study design. This is a cross-sectional study carried out in June 2021, during the off-season period, at the Alquería del Basket of Valencia Basket facilities, where included participants underwent a functional evaluation for anthropometric, neuromuscular and biomechanics outcomes and it was analyzed their relation to the single leg hop test.

Subjects. To have a homogeneous and representative sample of trainee-level elite female basketball athletes, subjects between 13 and 17 years old, belonging to the youth academy of different Spanish women's basketball first division were invited to participate in the study. A total of 90 athletes meeting these criteria agreed to participate in the study. Exclusion criteria to participate in the study was: (I) current acute injury receiving treatment, (II) non-surgical injuries to the lower limbs within the last 3 months; (III) surgical injuries to the lower limbs within the last 9 months; (IV) any other physical or psychological condition that altered the physical and functional status of the athletes, those conditions being based on the athlete's self-report or detected by the research staff.

Participants and parents/legal guardians gave their written informed consent to participate in the study, in accordance with the ethical guidelines of the Declaration of Helsinki and subsequent updates. This study obtained the ethical approval of the Ethics Committee of the Universitat de Valencia (UV-INV_ETICA-1523453). The research was developed and reported according to the recommendations of Strengthening the Reporting of Observational studies in Epidemiology (STROBE)²¹.

Procedure. The outcome assessment was performed in the aforementioned facilities by two physical therapists, with experience in the evaluation of these tests. Evaluations were all performed at the same day and by using the same equipment. Age and anthropometric data were obtained first for all participants. Before physical testing, athletes performed a 10-min general warm-up, consisting of medium-intensity aerobic exercises, mobility, and coordination. The physical tests were performed in the same order: Counter movement jump (CMJ), Y balance test (YBT) and single leg hop test, with a 2-min rest between them. Athletes were wearing sports clothes and shoes on. All tests were verbally explained, and a couple of attempts for each leg were allowed without recording results, to be familiarized with the test. Three valid measurements were taken from each test evaluation and the best one was registered.

Outcomes. *Counter movement jump.* To measure explosive strength, the CMJ test was used. To perform the test, participants initially stood on the platform, adopting a position of equal weight distribution between legs. Then, they were asked to perform a fast vertical jump, as high as possible, with both arms resting on the hips to avoid arm swing (Fig. 1). The data was collected with the Chronojump contact platform equipment, (Boscosystem®, Barcelona, Spain), registering the flight height (cm) and power (watts). The CMJ has proven extremely high reliability (ICC = 0.95)²², as well as Chronojump contact platform is considered a suitable equipment for its evaluation in elite athletes^{23,24}.



Figure 1. Procedure of the Countermovement jump test.

Y balance test. This is a validated simplified version of the original Star Excursion Balance Test, in which 3 of the 8 components of the originally proposed reaching directions (anterior displacement, postero-medial displacement and posterolateral displacement) are assessed. The test has reported excellent inter and intra-rater reliability scores (ICC of 0.88 and 0.90, respectively) in healthy population²⁵, and it is commonly used for the assessment of female basketball players²⁶. YBT is described as a dynamic balance assessment tool, although it also requires mobility, motor control and coordination of the lower limb.

To perform the test, three lines of tape were laid out on the floor so that one formed the anterior axis, and the other two were arranged at 135 degrees to it. Participants were asked to adopt a double-legged starting position, at the intersection of the 3 lines. The participants were asked to extend the contralateral leg to the one being assessed along one of the 3 components of the directions, as far as possible, without losing balance or altering the support position of the assessed leg (Fig. 2). Once the measurement of the 3 directions was completed, the same protocol was repeated with the opposite leg. The mean score for each leg was obtained by adding the scores of the three components and dividing by 3. The difference between the scores obtained for each leg was also calculated and expressed as a percentage (YBT interlimb difference).

Single-leg hop test. This functional test has proved to have excellent reliability, with intraclass correlation coefficients ranging from 0.92 to 0.96^{27,28}. The test was assessed according to the methodology described by Noyes et al.²⁹. A tape measure was placed on the ground, parallel to the surface set up for the jump. Athletes were asked to stand, first, on the dominant limb and perform a maximum-effort forward jump, landing on the same limb, without losing balance, changing the support surface, or marking extra supports for at least 3 s. If these criteria were not met, the test was considered invalid. When the test was valid, the distance covered by the jump was registered, expressed in centimeters. Hop symmetry index was calculated through: hop distance on the dominant limb / hop distance non-dominant limb.

Data analysis. Descriptive data included mean and standard error of mean of the used outcome. The normal distribution of data was checked the Kolmogorov–Smirnov test. A correlation study was performed between the single-leg hop test assessment (independent variable), and the rest of physical tests, anthropometric and age of participants, acting as dependent variables. Pearson’s R was used to explore the correlation of each of the dependent and independent parameters. The correlation effect size was interpreted as follows: <0.1, trivial; 0.11–0.3, low; 0.31–0.5, moderate; 0.51–0.7, large; 0.71–0.9, very large; >0.9, almost perfect³⁰. A linear regression model for dependent variables was created with all variables that exhibited significant correlations. Statistical data analysis was conducted using SPSS v26 (Inc., Chicago, IL, USA).



Figure 2. Y balance test procedure.

Informed consent for image publication. Informed consent from all subjects and/or their legal guardian(s) was obtained for publication of identifying information/images in an online open-access publication.

Results

Ninety healthy female basketball athletes (mean age: 15.1 (\pm 1.2) years) participated in the study. Table 1 show the descriptive values of the assessed results in the total sample, with the results of the anthropometric outcomes revealing athletes measure a mean of 1.69 (\pm 0.1) meters, weigh 58.33 (\pm 8.4) kg, and have a leg length of 0.84 (0.6) meters.

The results derived from the correlation study and predicting model scores represents a higher contribution of the lower-limb explosive strength (CMJ values) to the hop test results, as well as a lower contribution of the

Outcomes	Total sample (n = 90)
	Mean (SEM)
Anthropometric variables	
Age (years)	15.1 (1.22)
Height (m)	1.69 (0.11)
Weight (kg)	58.33 (8.40)
Body Mass Index	20.35 (2.63)
Leg length	0.84 (0.60)
Dominant leg (n (percentage))	
Right	82 (91.1%)
Left	8 (8.9%)
Single leg hop test	
Right leg (cm)	170.12 (25.6)
Left leg (cm)	169.86 (27.5)
Limb Symmetry Index (%)	- 0.41 (20.69)
Physical function variables	
Right YBT mean score (cm)	70.64 (9.32)
Left YBT mean score (cm)	70.41 (6.14)
Inter-limb YBT difference (%)	0.13 (0.10)
CMJ flight distance (cm)	22.45 (2.50)
CMJ flight power (w)	637.26 (78.08)

Table 1. Descriptive values for the total sample. YBT: Y Balance Test; CMJ: Counter Movement Jump.

dynamic balance (YBT-derived values). No significant relevance was found for the anthropometric outcomes in hop test results.

Table 2 shows the results for the correlation study. Significant correlation values were found for the YBT mean scores and the single leg hop test (both ipsilateral and contralaterally), with effect sizes that ranged from low to moderate (Right YBT mean score with right and left hop test: Pearson = 0.211 and 0.407; $p = 0.046$ and < 0.001 , respectively) (Left YBT mean score with right and left hop test: Pearson = 0.410 and 0.244; $p = < 0.001$ and 0.043, respectively). Likewise, from CMJ values, flight distance exhibited moderate effect size correlations with right (Pearson = 0.331; $p = 0.001$) and left hop test (Pearson = 0.313; 0.003) as well as flight power (Pearson = 0.385; $p = 0.001$; Pearson 0.367; $p = 0.001$). Correlations with anthropometric outcomes were not significant ($p > 0.05$).

The predicting model scores, displayed in Table 3, show that for right hop test, CMJ flight distance and power exhibited an adjusted determination coefficient of 0.408, ($\beta = 0.249$, $p = 0.013$), being of the outcomes analyzed, the ones that best explain the results for right hop test. For left hop test, again the CMJ values ($\beta = 0.229$, $p = 0.025$), and left YBT ($\beta = 0.331$, $p = 0.011$) jointly obtained an adjusted determination coefficient of 0.263.

Discussion

The hop test is a widely used tool for the functional assessment in athletes due to its easy and low-cost implementation, as well as its functional relevance^{9,28}. The main findings of the present study revealed that mainly CMJ-derived parameters, flight distance and power, determine the results of the hop test; as well as, to a lesser extent, dynamic balance levels. This contributes to a better understanding of the physical-functional components of the hop test and the interpretation of its results, highlighting that it has a multifactorial and not a unidimensional component, since different physical-functional aspects are integrated for its execution. Coaches, trainers and medical staff can benefit from these results, as it helps to design specific strategies for the improvement of these capacities, which will have an impact on the prevention of injuries and functional improvement of athletes.

Regarding dynamic balance, the results of the study demonstrated a correlation for the YBT with the hop test scores, both between the ipsilateral and the contralateral leg. Balance and postural control are key elements in the performance of functional movements in sport, and the alteration of these abilities has a negative impact on functional performance. In turn, dynamic balance, has been pointed out as a relevant factor in the prevention of sports injuries³¹. The capacity of dynamic balance would therefore be involved in the performance of the hop test, since a horizontal displacement of the center of masses will be produced, being necessary a correct stabilization process, especially during the flight and landing phase. In addition, stress on the dynamic balance will be

	Right single leg hop test	Left single leg hop test	Hop test interlimb
Dynamic balance outcomes			
Right YBT mean score	0.211 (0.046)*	0.407 (<0.001)*	-0.030 (0.783)
Left YBT mean score	0.410 (<0.001)*	0.244 (0.043)*	0.061 (0.569)
YBT interlimb	-0.129 (0.232)	-0.130 (0.224)	-0.129 (0.232)
Lower-limb Explosive force outcomes			
Flight distance (CMJ)	0.331 (0.001)*	0.313 (0.003)*	0.097 (0.367)
Flight Power (CMJ)	0.385 (0.001)*	0.367 (0.001)*	0.061 (0.438)
Anthropometric outcomes			
Length leg	0.183 (0.083)	0.103 (0.332)	0.070 (0.846)
Age	0.172 (0.104)	0.072 (0.502)	0.043 (0.687)
Height	0.124 (0.256)	0.107 (0.303)	0.081 (0.547)
Weight	0.034 (0.747)	0.018 (0.865)	0.035 (0.744)
BMI	-0.112 (0.292)	-0.058 (0.590)	0.067 (0.532)

Table 2. Correlation study for the total sample of the study (n = 90). Pearson correlation (p values). Significant values are in bold. YBT: Y Balance test; CMJ: Counter Movement Jump, BMI: Body Mass Index. * indicates p values < 0.05 .

Dependent variable	R ² adj	Predictor	β	p value
Hop test right	0.408	YBT right	-1.465	0.565
		YBT left	2.025	0.472
		CMJ	0.249	0.013*
Hop test left	0.263	YBT right	-0.023	0.850
		YBT left	0.331	0.011*
		CMJ	0.229	0.025*

Table 3. Predicting model values for dependent variables. Significant values are in bold. YBT: Y Balance test; CMJ: Counter Movement Jump. * indicates p values < 0.05 .

greater as it employs a one-legged landing. Furthermore, it has been suggested that the neuromuscular activity in vastus medialis and biceps femoris required to perform the hop test is similar to the one that occurs during dynamic stabilization activities^{32,33}. Boey & Lee highlighted that those higher levels of dynamic stability improve the biomechanics of landing in a one-legged hop³⁴. Likewise, Paterno et al. analyzed single-leg dynamic stability and postural control through a dynamometric platform, also suggesting the importance of those capacities for a greater achieved distance in the hop test³⁵, which would be in line with our results. However, the results obtained in the regression model limit the impact of dynamic balance as a component of the single leg hop test.

On the other hand, CMJ evaluates the explosive strength of the lower limb by requesting a stretch shortening cycle action to generate propulsive strength in a vertical jump. The vertical distance reached during the jump and the power generated are indicators of such explosive strength. We found a moderate correlation between the outcomes obtained in the CMJ and the single leg hop test. Moreover, the regression model verified that both CMJ flight distance and power influence the hop test results, and therefore, it could be postulated that explosive strength acts as a relevant physical-functional contributor to the results obtained in the single leg hop test. The relationship of lower-limb strength and the hop test has been analyzed primarily from isokinetic devices to assess muscle strength, with most of these studies revealing positive correlations^{13,15,36}. The CMJ offers another way to evaluate components of strength, with the main advantage that the generated strength is produced in a closed kinetic chain, and recreating a more functional movement, as well as with greater transference to sports activities in basketball. Therefore, the results of this study would complement those that, by means of isokinetic analysis, have reported a positive correlation between lower limb muscle strength and the results obtained in the hop test, offering a different dimension to evaluate strength, based on the stretch shortening cycle action.

Considering the physiology of the movement, we observe that both in the hop test and CMJ the movement is produced from the plyometric contraction of the lower limb, although with perpendicularly different vectors. This similarity in gesture could explain the influence of explosive strength, measured in a vertical jump, on the results of the hop test. But despite this apparent similarity, other authors point out that the physical demands experienced in both tests are different³⁷, reporting also different values in some cases, suggesting that the learning processes of the two types of jumps are different during the maturational stage³⁸. Specifically, some authors point out that hop test requires a more complex neuromuscular strategy to ensure stability during forward displacement³⁷ as well as others advocate that the physical demand is greater in the CMJ³⁹, so it has also been granted to be more sensitive when detecting functional deficiencies⁴⁰.

Based on the contribution of balance and explosive strength on the results of the hop test, it can be hypothesized that specific strategies to improve these conditions, such as balance or plyometric training will enhance the results of this test, and therefore influence the risk of injury and its functional capacity, as suggested in previous studies^{26,41}.

Age, perhaps surprisingly, was not found to significantly determine strength or balance levels in the subjects assessed. Participants in the present study age between 13 and 17 years old, so they are still in the maturation process. The maturation of the musculoskeletal system at these ages leads to an increase in physical capacities, such as muscle strength⁴². However, other studies challenge this assumption, such as the one conducted by Barber-Westin on 853 female athletes between 9 and 17 years of age, which found no consistent evidence of a linear relationship between the two factors⁴³. Therefore, although the chronological age of athletes seems to influence muscle strength levels, there are other maturational, biomechanical, and training aspects that are also relevant when explaining the evolution of physical capacities such as strength or dynamic stability⁴⁴. Precisely, the current literature debates the suitability of taking into account maturational age (through formulas such as peak height velocity) to the detriment of chronological age in studies carried out in pediatric and adolescent population⁴⁵.

The present analyses found that anthropometric outcomes were not statistically significant in the hop test result. Although it has been proposed that the results of the hop test should be expressed in relation to the length of the lower limb⁴⁶, the findings of the present study did not certify that assumption. A longer leg length means that a greater horizontal distance may be achieved. However, a greater lever arm in the lower limbs may also mean changes in neuromuscular activation patterns and biomechanics during jumping¹⁹. Even more so in maturational processes, where rapid growth can lead to greater adaptations having to be made. Yet this aspect should be further explored in future studies, it may be that at maturing ages, a greater length of the lower limbs does not necessarily entail a greater capacity for horizontal jumping.

Interlimb-hop differences are other common expression of the hop test results, due to its capacity to detect functional differences⁹. However, in the present study, no variables related to this result were found.

Strengths and limitations. Among the strengths of the study, it should be noted that the assessment was performed among a specific sample of young elite basketball players, with a considerable sample size. Furthermore, sophisticated assessment equipment, such as the Chronojump contact platform, was used.

However, the study presents certain limitations that should be considered. First, the influence of certain outcomes has been analyzed, focusing on those related to balance, explosive strength, and anthropometric factors, ignoring others that may also be relevant. Calculating maturational age of participants according to peak height velocity formula may be an interesting aspect for further studies. In addition, the cross-sectional nature of the study does not allow to establish cause-effect or extrapolation the results to different moments of the season.

Conclusions

Explosive strength, and dynamic balance although to a lesser extent, appear to be the most relevant physical-functional factors influencing the single leg hop test results among young elite female basketball athletes. These findings may serve as a basis to implement targeted interventions, such as plyometric and balance training, for an enhancement on functional rehabilitation and reducing the risk of injury related to the hop test results.

Data availability

Data available on request to corresponding author due to privacy/ethical restrictions.

Received: 14 December 2022; Accepted: 7 March 2023

Published online: 04 April 2023

References

- Hewett, T. E. *et al.* Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *Am. J. Sports Med.* **33**(4), 492–501. <https://doi.org/10.1177/0363546504269591> (2005).
- Newman, J. S. & Newberg, A. H. Basketball injuries. *Radiol. Clin. North Am.* **48**(6), 1095–1111. <https://doi.org/10.1016/j.rcl.2010.07.007> (2010).
- Bram, J. T., Magee, L. C., Mehta, N. N., Patel, N. M. & Ganley, T. J. Anterior cruciate ligament injury incidence in adolescent athletes: A systematic review and meta-analysis. *Am. J. Sports Med.* **49**(7), 1962–1972. <https://doi.org/10.1177/0363546520959619> (2021).
- Borowski, L. A., Yard, E. E., Fields, S. K. & Comstock, R. D. The epidemiology of US high school basketball injuries, 2005–2007. *Am. J. Sports Med.* **36**(12), 2328–2335. <https://doi.org/10.1177/0363546508322893> (2008).
- Maffulli, N., Longo, U. G., Gougoulas, N., Loppini, M. & Denaro, V. Long-term health outcomes of youth sports injuries. *Br. J. Sports Med.* **44**(1), 21–25. <https://doi.org/10.1136/bjsm.2009.069526> (2010).
- Ageberg, E. & Roos, E. M. The association between knee confidence and muscle power, hop performance, and postural orientation in people with anterior cruciate ligament injury. *J. Orthop. Sports Phys. Ther.* **46**(6), 477–482. <https://doi.org/10.2519/jospt.2016.6374> (2016).
- Gustavsson, A. *et al.* A test battery for evaluating hop performance in patients with an ACL injury and patients who have undergone ACL reconstruction. *Knee Surg. Sports Traumatol. Arthrosc. Off. J. ESSKA.* **14**(8), 778–788. <https://doi.org/10.1007/s00167-006-0045-6> (2006).
- Brumitt, J., Heiderscheit, B. C., Manske, R. C., Niemuth, P. E. & Rauh, M. J. Lower extremity functional tests and risk of injury in division iii collegiate athletes. *Int. J. Sports Phys. Ther.* **8**(3), 216–227 (2013).
- Clark, N. C. Functional performance testing following knee ligament injury. *Phys. Ther. Sport* **2**(2), 91–105. <https://doi.org/10.1054/ptsp.2001.0035> (2001).
- Kim, S. H., Lee, J. W., Kim, S. G., Cho, H. W. & Bae, J. H. Low rate of return to preinjury tegner activity level among recreational athletes: Results at 1 year after primary ACL reconstruction. *Orthop. J. Sports Med.* **9**(1), 2325967120975751. <https://doi.org/10.1177/2325967120975751> (2021).
- Caffrey, E., Docherty, C. L., Schrader, J. & Klossner, J. The ability of 4 single-limb hopping tests to detect functional performance deficits in individuals with functional ankle instability. *J. Orthop. Sports Phys. Ther.* **39**(11), 799–806. <https://doi.org/10.2519/jospt.2009.3042> (2009).
- Dingenen, B., Truijten, J., Bellemans, J. & Gokeler, A. Test-retest reliability and discriminative ability of forward, medial and rotational single-leg hop tests. *Knee* **26**(5), 978–987. <https://doi.org/10.1016/j.knee.2019.06.010> (2019).
- Xergia, S. A., Pappas, E. & Georgoulis, A. D. Association of the single-limb hop test with isokinetic, kinematic, and kinetic asymmetries in patients after anterior cruciate ligament reconstruction. *Sports Health.* **7**(3), 217–223. <https://doi.org/10.1177/1941738114529532> (2015).
- Greenberger, H. B. & Paterno, M. V. Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. *J. Orthop. Sports Phys. Ther.* **22**(5), 202–206. <https://doi.org/10.2519/jospt.1995.22.5.202> (1995).
- Temfemo, A., Hugues, J., Chardon, K., Mandengue, S. H. & Ahmaidi, S. Relationship between vertical jumping performance and anthropometric characteristics during growth in boys and girls. *Eur. J. Pediatr.* **168**(4), 457–464. <https://doi.org/10.1007/s00431-008-0771-5> (2009).
- Myer, G. D. *et al.* Utilization of modified NFL combine testing to identify functional deficits in athletes following ACL reconstruction. *J. Orthop. Sports Phys. Ther.* **41**(6), 377–387. <https://doi.org/10.2519/jospt.2011.3547> (2011).
- Rudolph, K. S., Axe, M. J. & Snyder-Mackler, L. Dynamic stability after ACL injury: who can hop?. *Knee Surg. Sports Traumatol. Arthrosc. Off. J. ESSKA.* **8**(5), 262–269. <https://doi.org/10.1007/s001670000130> (2000).
- Clark, N. C. & Mullally, E. M. Prevalence and magnitude of preseason clinically-significant single-leg balance and hop test asymmetries in an English adult netball club. *Phys. Ther. Sport Off. J. Assoc. Chart Physiother. Sports Med.* **40**, 44–52. <https://doi.org/10.1016/j.ptsp.2019.08.008> (2019).
- Laffaye, G., Wagner, P. P. & Tomblason, T. I. L. Countermovement jump height: Gender and sport-specific differences in the force-time variables. *J. Strength Cond. Res.* **28**(4), 1096–1105. <https://doi.org/10.1519/JSC.0b013e3182a1db03> (2014).
- Stanforth, P. R., Crim, B. N., Stanforth, D. & Stults-Kolehmainen, M. A. Body composition changes among female NCAA division I athletes across the competitive season and over a multiyear time frame. *J. Strength Cond. Res.* **28**(2), 300–307. <https://doi.org/10.1519/JSC.0b013e3182a20f06> (2014).
- Cuschieri, S. The STROBE guidelines. *Saudi J. Anaesth.* **13**(Suppl 1), S31–S34. https://doi.org/10.4103/sja.SJA_543_18 (2019).
- Wadhi, T., Rauch, J. T., Tamulevicius, N., Andersen, J. C. & De Souza, E. O. Validity and reliability of the GymAware linear position transducer for squat jump and counter-movement jump height. *Sports Basel Switz.* **6**(4), E177. <https://doi.org/10.3390/sports6040177> (2018).
- Pueo, B., Penichet-Tomas, A. & Jimenez-Olmedo, J. M. Reliability and validity of the Chronojump open-source jump mat system. *Biol. Sport.* **37**(3), 255–259. <https://doi.org/10.5114/biolisport.2020.95636> (2020).
- Gonzalo-Skok, O., Arjol-Serrano, J. & Suarez-Arrones, L. Impact of a warm-up and different small sided games drills on jump performance in elite young basketball players. *J. Sport Health Res.* **6**, 87–98 (2014).
- Powden, C. J., Dodds, T. K. & Gabriel, E. H. The reliability of the star excursion balance test and lower quarter y-balance test in healthy adults: A systematic review. *Int. J. Sports Phys. Ther.* **14**(5), 683–694 (2019).
- Benis, R., Bonato, M. & La Torre, A. L. Elite female basketball players' body-weight neuromuscular training and performance on the Y-balance test. *J. Athl. Train.* **51**(9), 688–695. <https://doi.org/10.4085/1062-6050-51.12.03> (2016).
- Bolgia, L. A. & Keskula, D. R. Reliability of lower extremity functional performance tests. *J. Orthop. Sports Phys. Ther.* **26**(3), 138–142. <https://doi.org/10.2519/jospt.1997.26.3.138> (1997).
- Bandy, W. D., Rusche, K. R. & Tekulve, F. Y. Reliability and limb symmetry for five unilateral functional tests of the lower extremities. *Isokinet. Exerc. Sci.* **4**(3), 108–111. <https://doi.org/10.3233/IES-1994-4304> (1994).
- Noyes, F. R., Barber, S. D. & Mangine, R. E. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am. J. Sports Med.* **19**(5), 513–518. <https://doi.org/10.1177/036354659101900518> (1991).
- Gignac, G. E. & Szodorai, E. T. Effect size guidelines for individual differences researchers. *Pers. Individ. Differ.* **102**, 74–78. <https://doi.org/10.1016/j.paid.2016.06.069> (2016).
- Hewett, T. E., Torg, J. S. & Boden, B. P. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br. J. Sports Med.* **43**(6), 417–422. <https://doi.org/10.1136/bjsm.2009.059162> (2009).

32. Lee, D. K., Kim, G. M., Ha, S. M. & Oh, J. S. Correlation of the Y-balance test with lower-limb strength of adult women. *J. Phys. Ther. Sci.* **26**(5), 641–643. <https://doi.org/10.1589/jpts.26.641> (2014).
33. Huston, L. J. & Wojtys, E. M. Neuromuscular performance characteristics in elite female athletes. *Am. J. Sports Med.* **24**(4), 427–436. <https://doi.org/10.1177/036354659602400405> (1996).
34. Boey, D. & Lee, M. The relationship between Y-balance test scores and knee moments during single-leg jump-landing in netball. *Int. J. Sports Phys. Ther.* **15**(5), 722–731. <https://doi.org/10.26603/ijst20200722> (2020).
35. Paterno, M. V. *et al.* Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am. J. Sports Med.* **38**(10), 1968–1978. <https://doi.org/10.1177/0363546510376053> (2010).
36. Petschnig, R., Baron, R. & Albrecht, M. The relationship between isokinetic quadriceps strength test and hop tests for distance and one-legged vertical jump test following anterior cruciate ligament reconstruction. *J. Orthop. Sports Phys. Ther.* **28**(1), 23–31. <https://doi.org/10.2519/jospt.1998.28.1.23> (1998).
37. Murtagh, C. F. *et al.* The neuromuscular determinants of unilateral jump performance in soccer players are direction-specific. *Int. J. Sports Physiol. Perform.* **13**(5), 604–611. <https://doi.org/10.1123/ijstpp.2017-0589> (2018).
38. Scruggs, P. W., Beveridge, S. K. & Watson, D. L. Increasing children's school time physical activity using structured fitness breaks. *Pediatr. Exerc. Sci.* **15**(2), 156–169. <https://doi.org/10.1123/pes.15.2.156> (2003).
39. Bishop, C., Read, P., McCubbine, J. & Turner, A. 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. <https://doi.org/10.1519/JSC.00000000000002544> (2021).
40. Ebert, J. R. *et al.* Comparison of the 'BACK IN ACTION' test battery to standard hop tests and isokinetic knee dynamometry in patients following anterior cruciate ligament reconstruction. *Int. J. Sports Phys. Ther.* **13**(3), 389–400 (2018).
41. Beato, M., Bianchi, M., Coratella, G., Merlini, M. & Drust, B. Effects of plyometric and directional training on speed and jump performance in elite youth soccer players. *J. Strength Cond. Res.* **32**(2), 289–296. <https://doi.org/10.1519/JSC.00000000000002371> (2018).
42. Malina, R. M. Weight training in youth-growth, maturation, and safety: An evidence-based review. *Clin. J. Sport Med.* **16**(6), 478. <https://doi.org/10.1097/01.jsm.0000248843.31874.be> (2006).
43. Barber-Westin, S. D., Noyes, F. R. & Galloway, M. Jump-land characteristics and muscle strength development in young athletes: A gender comparison of 1140 athletes 9 to 17 years of age. *Am. J. Sports Med.* **34**(3), 375–384. <https://doi.org/10.1177/0363546505281242> (2006).
44. Barber-Westin, S. D., Galloway, M., Noyes, F. R., Corbett, G. & Walsh, C. Assessment of lower limb neuromuscular control in prepubescent athletes. *Am. J. Sports Med.* **33**(12), 1853–1860. <https://doi.org/10.1177/0363546505278257> (2005).
45. Malina, R. M., Rogol, A. D., Cumming, S. P., Coelho e Silva, M. J. & Figueiredo, A. J. Biological maturation of youth athletes: assessment and implications. *Br. J. Sports Med.* **49**(13), 852–859. <https://doi.org/10.1136/bjsports-2015-094623> (2015).
46. Büttner, F. *et al.* Using functional movement tests to investigate the presence of sensorimotor impairment in amateur athletes following sport-related concussion: A prospective, longitudinal study. *Phys. Ther. Sport.* **47**, 105–113. <https://doi.org/10.1016/j.ptsp.2020.10.012> (2021).

Author contributions

F.D.N., P.C. and J.Cal. carried out the conception and design of the study. F.D.N., J.Cas. and B.R.L. drafted the main text of the manuscript. B.P.D. performed the statistical analysis and prepared the tables. All authors reviewed the final version of the manuscript and gave their consent for publication.

Funding

The present research did not receive any financial support.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to J.C.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2023

Terms and Conditions

Springer Nature journal content, brought to you courtesy of Springer Nature Customer Service Center GmbH (“Springer Nature”).

Springer Nature supports a reasonable amount of sharing of research papers by authors, subscribers and authorised users (“Users”), for small-scale personal, non-commercial use provided that all copyright, trade and service marks and other proprietary notices are maintained. By accessing, sharing, receiving or otherwise using the Springer Nature journal content you agree to these terms of use (“Terms”). For these purposes, Springer Nature considers academic use (by researchers and students) to be non-commercial.

These Terms are supplementary and will apply in addition to any applicable website terms and conditions, a relevant site licence or a personal subscription. These Terms will prevail over any conflict or ambiguity with regards to the relevant terms, a site licence or a personal subscription (to the extent of the conflict or ambiguity only). For Creative Commons-licensed articles, the terms of the Creative Commons license used will apply.

We collect and use personal data to provide access to the Springer Nature journal content. We may also use these personal data internally within ResearchGate and Springer Nature and as agreed share it, in an anonymised way, for purposes of tracking, analysis and reporting. We will not otherwise disclose your personal data outside the ResearchGate or the Springer Nature group of companies unless we have your permission as detailed in the Privacy Policy.

While Users may use the Springer Nature journal content for small scale, personal non-commercial use, it is important to note that Users may not:

1. use such content for the purpose of providing other users with access on a regular or large scale basis or as a means to circumvent access control;
2. use such content where to do so would be considered a criminal or statutory offence in any jurisdiction, or gives rise to civil liability, or is otherwise unlawful;
3. falsely or misleadingly imply or suggest endorsement, approval, sponsorship, or association unless explicitly agreed to by Springer Nature in writing;
4. use bots or other automated methods to access the content or redirect messages
5. override any security feature or exclusionary protocol; or
6. share the content in order to create substitute for Springer Nature products or services or a systematic database of Springer Nature journal content.

In line with the restriction against commercial use, Springer Nature does not permit the creation of a product or service that creates revenue, royalties, rent or income from our content or its inclusion as part of a paid for service or for other commercial gain. Springer Nature journal content cannot be used for inter-library loans and librarians may not upload Springer Nature journal content on a large scale into their, or any other, institutional repository.

These terms of use are reviewed regularly and may be amended at any time. Springer Nature is not obligated to publish any information or content on this website and may remove it or features or functionality at our sole discretion, at any time with or without notice. Springer Nature may revoke this licence to you at any time and remove access to any copies of the Springer Nature journal content which have been saved.

To the fullest extent permitted by law, Springer Nature makes no warranties, representations or guarantees to Users, either express or implied with respect to the Springer nature journal content and all parties disclaim and waive any implied warranties or warranties imposed by law, including merchantability or fitness for any particular purpose.

Please note that these rights do not automatically extend to content, data or other material published by Springer Nature that may be licensed from third parties.

If you would like to use or distribute our Springer Nature journal content to a wider audience or on a regular basis or in any other manner not expressly permitted by these Terms, please contact Springer Nature at

onlineservice@springernature.com