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# Masterclass: Are you getting the most out of your triple hop testing?

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ABSTRACT

The triple hop test is a widely used, practical tool that allows physical therapists to assess an athlete's readiness to return-to-sport (RTS) following injury. However, recent consensus statements have raised concerns that hop distance alone may be insufficient to capture the complexity of functional recovery or to fully assess inter-limb symmetry, potentially masking readiness and increasing the risk of reinjury. In this Masterclass: exemplar kinetic and kinematic data for the triple hop are detailed; the utility of the quintuple hop introduced; the distinction between outcome and movement strategy variables discussed within an asymmetry context; and, the integration of accessible, cost-effective technologies within a tier-based framework for RTS assessment outlined. The aim of the article is to enhance the evaluation of movement strategies and support clinicians in making more informed and confident RTS decisions.

## 1. Introduction

A structured and systematic rehabilitation process is critical for facilitating a successful RTS process following injury (Creighton et al., 2010; Shrier, 2015). Such a process should restore physical capabilities and foster athlete confidence to resume pre-injury levels of competition. Moreover, for athletes in environments with access to pre-injury musculoskeletal screening, this information should be utilised to inform effective RTS strategies and to set the criteria for late-stage rehabilitation testing, with an aim of reaching pre-injury physical performance measures (Cooke et al., 2025; Kotsifaki et al., 2023). To achieve this, consideration for RTS protocols must incorporate a comprehensive assessment of factors, including prior injury history, current functional capacity and future needs analysis, sport-specific risk exposure, and psychosocial readiness (Ardern et al., 2016; Baez et al., 2023; Buckthorpe et al., 2024). Within the domain of lower limb injuries, RTS frameworks have predominantly focused on rehabilitation following anterior cruciate ligament reconstruction (ACLR) (Barber-Westin & Noyes, 2011; Kotsifaki & Whiteley, 2023), meniscal injuries (Culvenor et al., 2022), and hamstring strains (Macdonald et al., 2019; van der Horst et al., 2017). This emphasis is attributable primarily to the high incidence of these injuries and their significant impact on training continuity and return to competitive participation (Ardern et al., 2016), as well as the prevalence of reinjury (Kyritsis et al., 2016).

Criteria-based RTS protocols and decision-making frameworks are designed to reduce risk for individuals returning to pre-injury activities (Grindem et al., 2016; Kyritsis et al., 2016), with the risk of reinjury being understood as multifactorial; including time, sex, age, strength deficits, proprioceptive control, and biomechanical changes (Fulton et al., 2014). These protocols typically incorporate objective assessments of muscular strength, tests for neuromuscular control (e.g., single leg hop for distance, triple cross-over hop, triple hop, 6 m timed hop) (Grindem et al., 2016; Kyritsis et al., 2016), as well as subjective assessments through qualitative questionnaires to evaluate functional performance and limb symmetry (Ardern et al., 2016; Gokeler, Welling, Zaffagnini, et al., 2017; Grindem et al., 2016; Kotsifaki et al., 2023; Kotsifaki & Whiteley, 2023). Achieving a "pass" on RTS assessments has been associated with lower rates of knee injury (Grindem et al., 2016; Kyritsis et al., 2016), specifically for secondary anterior cruciate ligament (ACL) injuries (Grindem et al., 2016; Kyritsis et al., 2016; Raoul et al., 2019; Webster & Feller, 2019; Zhou et al., 2024), and graft ruptures (Figueroa Poblete et al., 2025; Kyritsis et al., 2016). However, it must be noted that, particularly in ACLR, these reduced rates of reinjury are conflicting in the literature (Losciale et al., 2019; Sousa et al., 2017; Zhou et al., 2024), and could also be associated with an elevated risk of ACL injury to the contralateral limb (Zhou et al., 2024). Of the tests identified in the literature as suitable and frequently used in physiotherapeutic practice for tracking progress and determining clearance for higher-intensity activities such as sprinting and change of direction, the triple hop test has been shown to be reliable when used with athletic

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populations (Šarabon et al., 2022). This RTS test serves as the focus of this article.

Triple hop distance is commonly used by clinicians as a key metric to assess lower limb function, with inter-limb comparisons informing the magnitude of symmetry. This is often expressed as the limb symmetry index (LSI), calculated by comparing the distance achieved by the injured limb relative to the uninjured limb (Gokeler, Welling, Zaffagnini, et al., 2017; Noyes et al., 1991). Researchers however, have questioned the utility of LSI derived solely from hop distance as an adequate indicator of readiness for RTS (Gokeler, Welling, Benjaminse, et al., 2017; Wellsandt et al., 2017). Hop distance is the outcome variable and is determined by several biomechanical factors all of which should be evaluated independently where possible. Hop distance may obscure underlying biomechanical deficits, particularly in propulsive and braking force asymmetries (Kotsifaki et al., 2022; White et al., 2021). For example, while hop distance LSI values may fall within acceptable thresholds of <15 % asymmetry for both reinjury risk and performance (Barber-Westin & Noyes, 2011; Bishop et al., 2018) (e.g., 97 %), Kotsifaki et al. (2022) reported persistent asymmetries in joint contributions during both propulsive (69 % symmetry) and braking phases (87 % symmetry) of movements in individuals post-ACL reconstruction (Kotsifaki et al., 2022). These findings underscore the importance of incorporating a more comprehensive approach to evaluating jump/hop performance to avoid overlooking clinically relevant compensations.

Hop distance measures alone seem insufficient as standalone criteria to inform RTS decisions following lower limb injuries, and maybe other measures can yield more nuanced insights into athlete RTS. This article aims to provide clinical practitioners with a more in-depth examination of multiple hop testing, outlining its clinical utility, interpretive value, asymmetry, and practical implementation for late-stage RTS. Additionally, the discussion will include recent technological advancements that could be considered during testing that will enhance diagnostic capability across diverse clinical settings and budgetary constraints.

## 2. Biomechanics of horizontal multiple hops in series

### 2.1. Triple hop

Horizontal multiple hops in series consist of a series of unilateral propulsive and braking efforts, showcasing an athlete's capacity for repetitive efforts of single-leg reactive strength. A typical force signal for a triple hop is shown in Fig. 1 with typical force data and outcome measures in Tables 1 and 2. The forces have been delineated into vertical and horizontal forces. Note that the vertical and horizontal forces have been divided further into braking (decelerative or eccentric) and propulsive (accelerative or concentric) forces. The within-braking-phase peak forces are usually classified as landing or impact peaks. Each hop

**Table 1**
Example force data during a horizontal triple hop for vertical and horizontal braking and propulsion phases.

| | Ground Contact 1 Mean ± SD | Ground Contact 2 Mean ± SD |
|---|---|---|
| Max Vertical Force (N.kg) | 32.5 ± 4.6 | 42.0 ± 7.60 |
| Vertical Impulse (N.kg) | 5.67 ± 0.44 | 5.87 ± 0.34 |
| Vertical Braking Impulse (Ns.kg) | 1.34 ± 0.63 | 2.58 ± 0.46 |
| Vertical Propulsive Impulse (Ns.kg) | 4.36 ± 0.43 | 3.32 ± 0.48 |
| Horizontal Impulse (N.kg) | 0.70 ± 0.16 | 0.30 ± 0.15 |
| Horizontal Braking Impulse (Ns.kg) | 0.05 ± 0.02 | 0.19 ± 0.05 |
| Horizontal Propulsive Impulse (Ns.kg) | 0.76 ± 0.13 | 0.50 ± 0.11 |

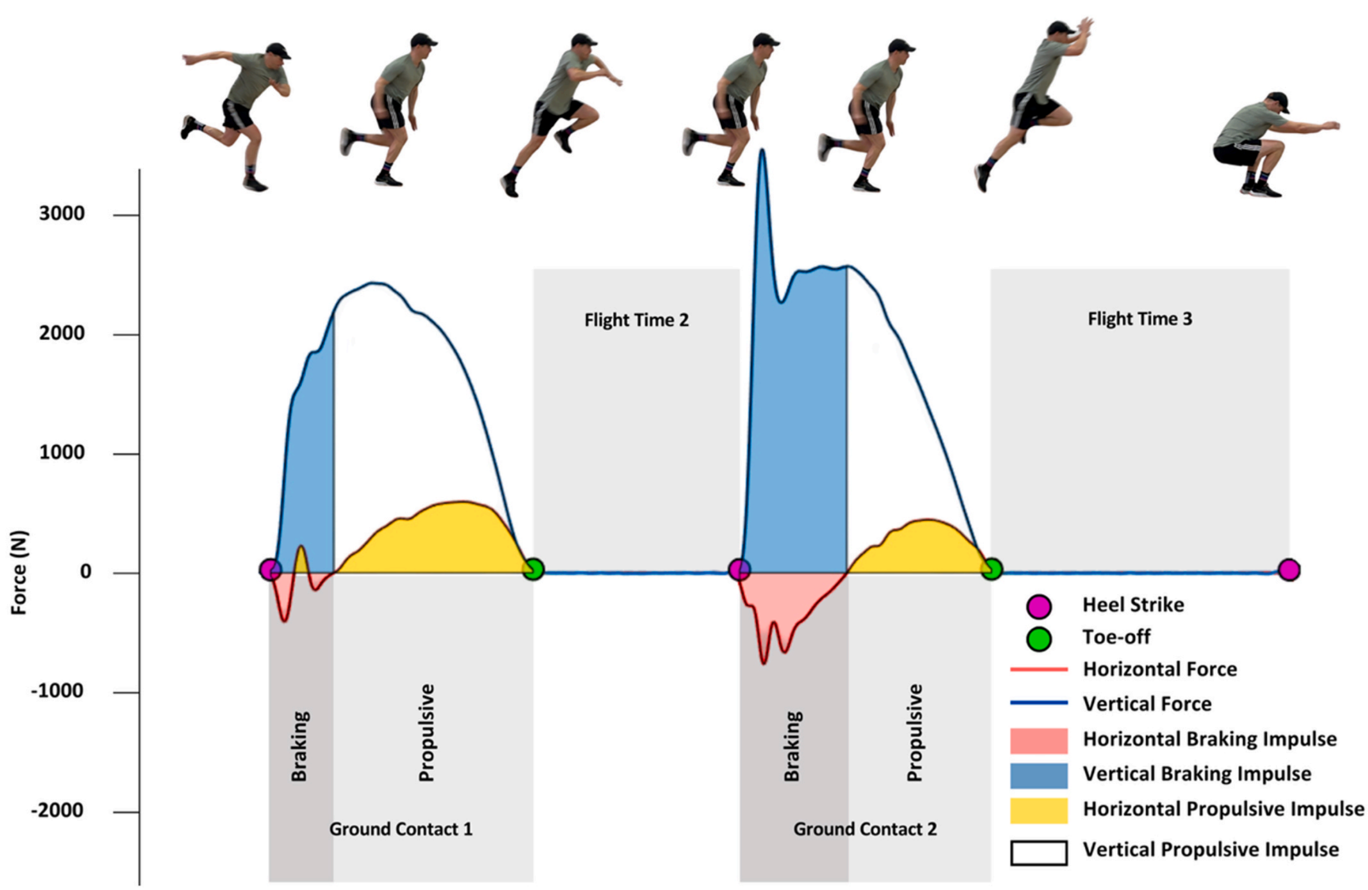


**Fig. 1.** The propulsive and braking phases of a triple hop (3 steps) and associated vertical and horizontal forces.

**Table 2**
Example kinematic outcome measures during a horizontal triple hop.

| | 1 Mean ± SD | 2 Mean ± SD | 3 Mean ± SD | Total Mean ± SD |
|---|---|---|---|---|
| Flight Time (s) | 0.28 ± 0.03 | 0.33 ± 0.04 | 0.44 ± 0.05 | – |
| Ground Contact Time (s) | 0.28 ± 0.03 | 0.26 ± 0.03 | – | – |
| Hop Distance (m) | 1.69 ± 0.15 | 2.03 ± 0.23 | 2.73 ± 0.31 | 6.48 ± 0.63 |
| Reactive Strength Index ($RSI_{horDIST}$) | 7.26 ± 1.39 | 10.71 ± 2.18 | – | 11.99 ± 2.21 |
| Reactive Strength Index ($RSI_{horFT}$) | 1.18 ± 0.25 | 1.72 ± 0.34 | – | 1.44 ± 0.28 |

involves a combination of vertical and horizontal propulsive impulses (force x the time over which the force acts), determining take-off velocity and subsequent hop distance. During landing phases, vertical and horizontal braking impulses are generated as the athlete decelerates, stabilises, and repositions the body for the next hop, all while attempting to preserve forward momentum within the limits of their neuromuscular capacity (see Fig. 1). This downward decelerative loading is accompanied by stretching or lengthening of the musculotendinous structures and is known as a stretch-load.

Vertical and horizontal stretch-loads increase with successive jumps due to increased forces (Table 1) over shorter ground contacts (Table 2). The braking phase or landing phase, where significant force dissipation and eccentric rate of force development (RFD) are required, is usually where injured athletes in late-stage RTS can show large functional deficits if not considered in programming (Buckthorpe et al., 2019) and could result in greater risk of exposure to reinjury if not addressed (Buckthorpe & Roi, 2017). Insufficient eccentric RFD and dynamic lower limb control, aside from limited exposure to appropriate strength programming, could also result from impaired recruitment of high-threshold motor units due to mechanoreceptor damage, especially after ACL reconstruction. (Buckthorpe et al., 2019, 2024). Furthermore, the knee extensor muscles are biomechanically disadvantaged because of reduced actin–myosin filament overlap during knee end-range extension, leading to a decreased contribution to maximal knee joint torque (Bremner et al., 2015; Cavalcante et al., 2021; Scott et al., 2021). As a result, the knee compensates by relying more heavily on endo- and exo-sarcomeric connective tissues and other passive elastic elements, which might also be in a state of recovery given a longer time course for adaptation post-injury. These increases in stretch-load between the first and second ground contacts of a triple hop, particularly in vertical (2x) and horizontal (~4x) braking demands, can be seen in Fig. 1 and Table 1.

### 2.2. *Quintuple hop*

For physiotherapists who have higher-functioning athletes, it is suggested that a quintuple hop may provide a means to test the athlete's ability to tolerate higher stretch-load demands that may be more indicative of sport. Anecdotally, the authors have noted that many athletes exhibit good coordination in triple hops; however, with higher stretch-loads, for some individuals there is a loss of coordination in hopping rhythm, likely due to inadequate strength to handle such braking forces, which in turn affects the utility of the test. For example, vertical ground reaction force increases by approximately 14 % between successive contacts during triple and quintuple hop tests, ranging from 3.3x to 5.1x body weight from the first to the fourth ground contact (Fig. 2) (Sharp et al., 2025c). With successive hops, the demand on the tissues and structures responsible for vertical eccentric braking forces (plantar-flexors, vasti muscle group) of the lower limbs increases by approximately 32 % to counter the body's downward momentum, while the horizontal braking demand (dorsi-flexors, hamstrings, gluteals) increases by approximately 56 % (Sharp et al., 2025c). This indicates that the foot, during landing, is likely touching down further in front of the line of the centre of mass (CoM), a result of the system's need to produce greater forces to prevent collapse to the ground. The increased percentage contribution of both vertical and horizontal braking contributions to 'net impulse' for both triple and quintuple hops with successive contacts can be observed in Fig. 3. With the increase in braking demand, there is a decrease in vertical (21–24 %) and horizontal (40–57 %) propulsive output between the first and last hops, likely due to the body's capacity to produce force during shorter ground contact time, a result of the increased velocity in the body's CoM.

## 3. Asymmetry

Due to the increased stretch-load demands of the quintuple-hop, the associated elevation in injury risk may be unjustified as a form of RTS assessment. This risk must be considered in the context of the individual's status and functional capacity and the anticipated physical demands of their sport upon return. Fig. 4 provides a framework for decision-making specific to the variables of interest and introduces the

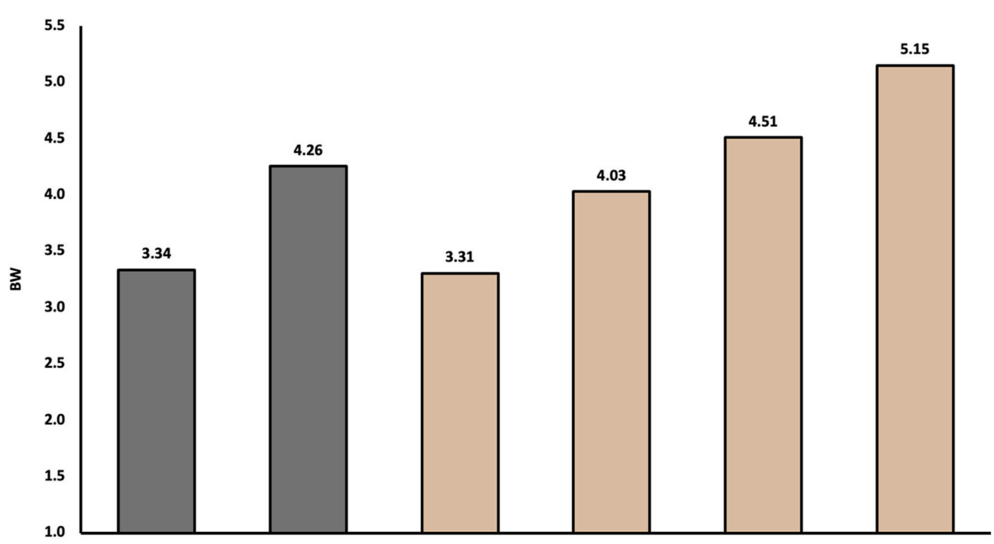


**Fig. 2.** Vertical force shown in bodyweight (BW) across hops.

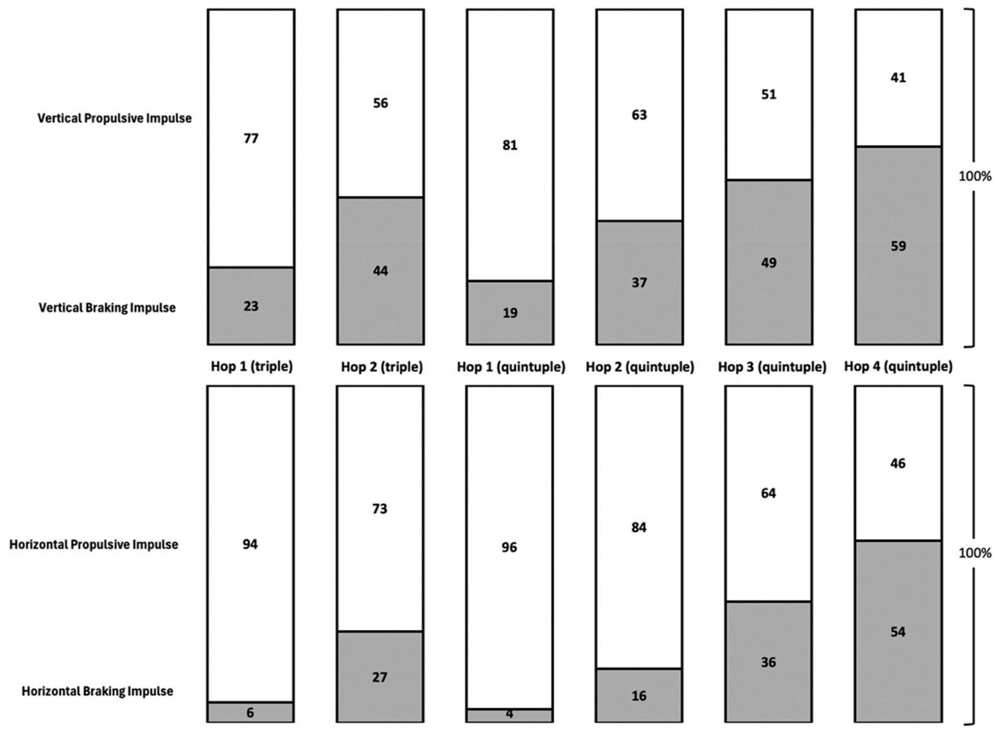


**Fig. 3.** Percentage contribution of vertical and braking impulse towards net vertical and anterior-posterior impulse across horizontal multiple hops.

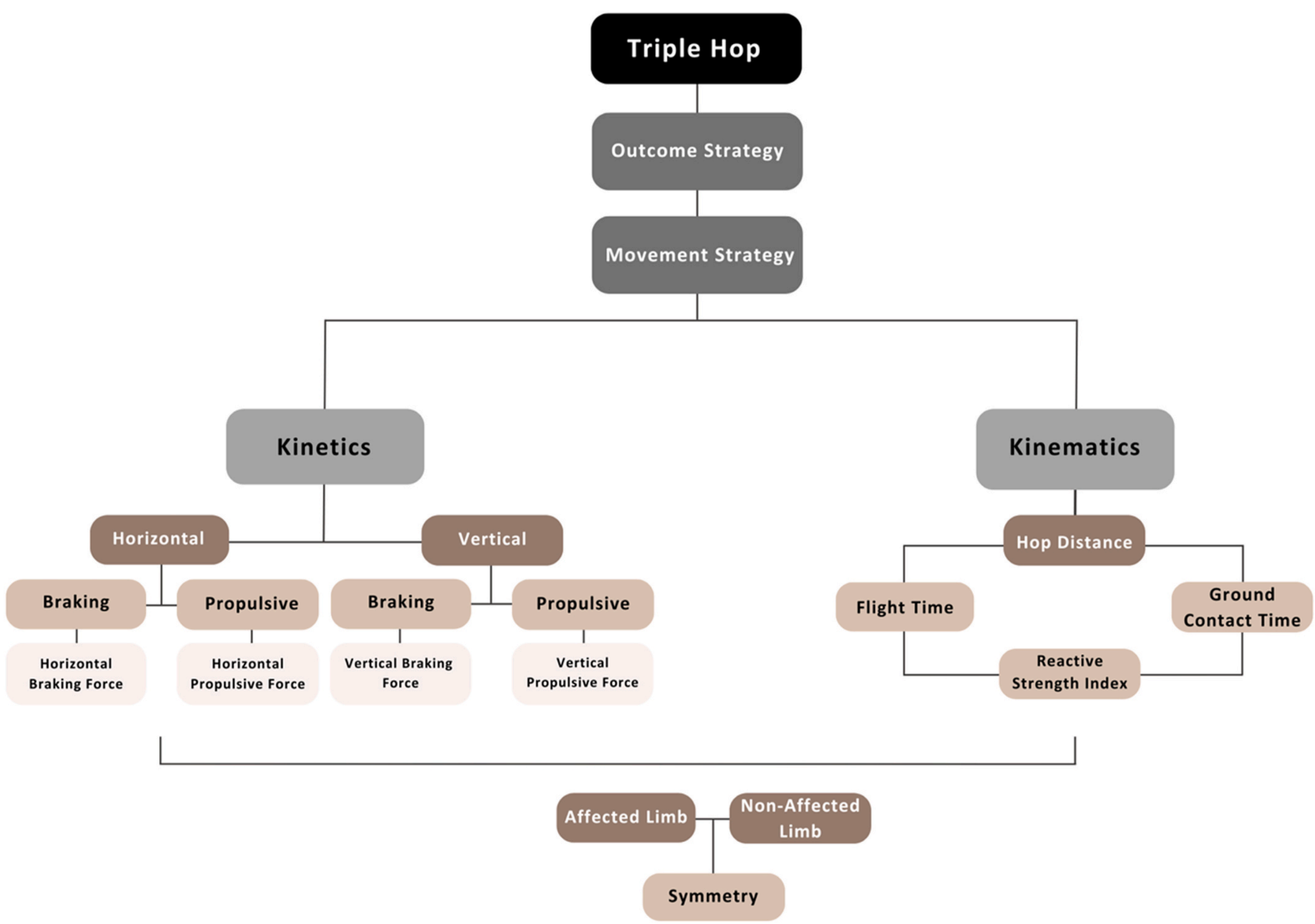


**Fig. 4.** Deterministic model of triple hop performance.

concept of outcome versus movement strategy variables. The technology required to assess these variables is discussed later in this article. Many RTS protocols emphasise outcome-based metrics, such as hop distance, without considering the underlying movement strategies that influence these outcomes. Key determinants of a movement strategy include the kinetic components of vertical and horizontal braking and propulsive forces/impulses, which affect kinematic factors such as flight duration and ground contact time during each hop, which in turn are affected by the range of motion of the trunk, hip, knee and ankle (dos Reis et al., 2015). A more granular analysis of these kinetic and kinematic factors offers deeper insight into the athlete's functional status and helps identify specific deficits that may need to be addressed to facilitate successful RTS, because as previously highlighted, outcome-based measures like hop distance may not fully capture underlying joint work asymmetries or compensatory movement patterns.

The reactive strength index in the horizontal plane ($RSI_{hor}$), typically calculated as hop distance ($RSI_{horDIST}$) or flight time ($RSI_{horFT}$) divided by ground contact time across multiple hops, has been shown to correlate strongly with sprinting and change-of-direction performance (Sharp et al., 2025b; Šarabon et al., 2022) and is a useful variable to assess and monitor. RSI is considered a fundamental determinant of various athletic qualities (Jarvis et al., 2022) and, due to its demonstrated reliability, particularly within the context of triple hop assessments, is a valuable addition to the RTS test battery (Davey et al., 2021). Because $RSI_{hor}$ is a function of both flight time and distance (both reflective of propulsive force application) and ground contact time (which encompasses the braking phase, CoM repositioning, and subsequent force generation), it offers a complementary assessment of lower-limb reactive strength than flight time or ground contact time in isolation. Caution is warranted however when interpreting ratio-derived measures such as the RSI, and even more so for LSI, which introduces an additional layer of complexity. To accurately interpret changes in these variables and support evidence-based decision-making, it is essential to also examine their underlying components, such as ground contact time, flight time, and displacement (Bishop, 2025).

As can be observed in Fig. 4, one of the outcome measures of the triple hop (usually hop distance) is determined by movement strategies that are essentially a combination of kinetic and kinematic factors. In essence, limb symmetry indexes (Noyes et al., 1991) could be quantified on any number of these measures, depending on the technology available and the focus of the assessment. The LSI compares dominant versus non-dominant or affected versus non-affected limbs and is used to determine readiness for RTS and can include assessments of strength, reactive strength index, endurance, change-of-direction/agility, and landing mechanics (Cooper & Hughes, 2018; Figueroa Poblete et al., 2025; Gokeler, Welling, Zaffagnini, et al., 2017; Noyes et al., 1991; Zarro et al., 2023). The single-leg hop, triple hop, and crossover hop as common methods for assessing horizontal symmetry (Davey et al., 2021; Kotsifaki et al., 2022; Lloyd et al., 2020; Munro & Herrington, 2011; Sarabon et al., 2023).

Recent insight from the Aspetar Orthopaedic and Sports Medicine Group challenges the clinical utility of distance-based measures and their associated symmetry indices in assessing biomechanical knee function following ACLR. As previously mentioned, although LSI values for hop distance may indicate acceptable levels of asymmetry (<15 %), individuals after ACL reconstruction often continue to show significant imbalances in joint mechanics and particularly during the propulsive phase (with only 69 % symmetry) and the braking phase (87 % symmetry), even though hop distance LSI was as high at 97 % (Kotsifaki et al., 2022). Notable deficits in knee peak flexion angle (~9 %), knee extensor moments (~14 %), and increased knee adduction moments (~17 %) have been observed in elite runners following ACLR, even after completion of RTS programs and successfully achieving performance test outcomes (Alarifi et al., 2025). Outcome measures such as distance fail to capture joint-specific contributions to movement and do not accurately reflect the functional capacity of the knee joint. Notably, during the propulsive phase of a hop, approximately 10–14 % of the work is performed by the knee, with the remaining 88 % attributed to the hip and ankle (Kotsifaki et al., 2022). Sharp et al. (2025) found greater individual asymmetries in kinetic variables, particularly braking impulse asymmetries as high as 95.4 % (Sharp et al., 2025a), most likely due to differing braking movement strategies and/or eccentric force capability (Hovey et al., 2021), with the greatest asymmetry only 12.7 % in hop distance and 9.3 % in total hop distance performed. These findings underscore the inadequacy of distance alone as a surrogate for assessing knee function and highlight the need for more joint-specific biomechanical analyses in RTP decision-making (Kotsifaki & Whiteley, 2023). Furthermore, the reader needs to be cognisant that when reviewing the literature, average asymmetry differences across groups can be trivial to small; however, substantial within-group variability in many cases can be observed. Moreover, the direction of asymmetry often fluctuates between individuals, underscoring the need for individualised data analysis rather than reliance on group means alone (Davey et al., 2021).

## 4. Technology integration for better diagnostics

The diagnostic information available to practitioners is inherently limited by the technologies accessible within their environments. Many of the advanced measures discussed previously can only be determined in a laboratory setting, such as asymmetry metrics derived from in-ground force platforms, and are often impractical in routine clinical or field settings due to their high cost and substantial infrastructure requirements. To address this limitation, this section introduces technologies that can be used to measure the kinematic and kinetic variables detailed in Fig. 4, which should in turn enhance the diagnostic utility of multiple hop testing.

A systematic framework for technology integration, mapping each tool to its diagnostic capabilities, is detailed in Fig. 5. The diagram showcases the progression from low-cost tech to "gold standard" options. Increasingly, low-cost technologies are becoming available to practitioners, enabling the collection of meaningful, high-quality data that can inform clinical decision-making.

Tier 1 assessment involves traditional methods for assessing triple hop performance, such as using a measuring tape. A standardized warm-up and assessment protocol, detailed in the Supplementary Material, ensures consistency and reliability in measurement. The hopping sequence is illustrated in Fig. 6. This method allows for the evaluation of overall hop performance via total distance covered, as well as limb symmetry by comparing outcomes between the affected and unaffected limbs.

Tier 2 assessments incorporate videographic assessment in conjunction with a measuring tape to enhance the evaluation of hop performance. Video-based assessments using a smartphone recording at 120 frames per second (fps) or tablet have been found to be both valid and reliable for triple and quintuple hop testing, enabling detailed analysis of each hop phase (Sharp et al., 2023, 2024), but with higher frame rates of 240 fps readily available this will likely provide a very high correlation with infrared motion capture in jump detection (Balsalobre et al., 2014). For optimal recording, the device should be mounted on a tripod approximately 30 cm above the ground and positioned 14 m from the start line for the triple hop or 19 m for the quintuple hop. Adequate lighting conditions are crucial for accurately detecting key events, such as heel strike and toe-off. The recorded footage can be analysed using open-access motion analysis software, such as Kinovea (https://www.kinovea.org), which has a high level of functionality to measure temporal events (flight and contact times), as well as joint kinematics through manual annotation.

Tier 3 assessments can provide automated detection of hop kinematics utilising inertial measurement units (IMUs), which present a non-invasive, field-friendly option for assessing the mechanical demands of hopping tasks and have shown to have acceptable levels of reliability

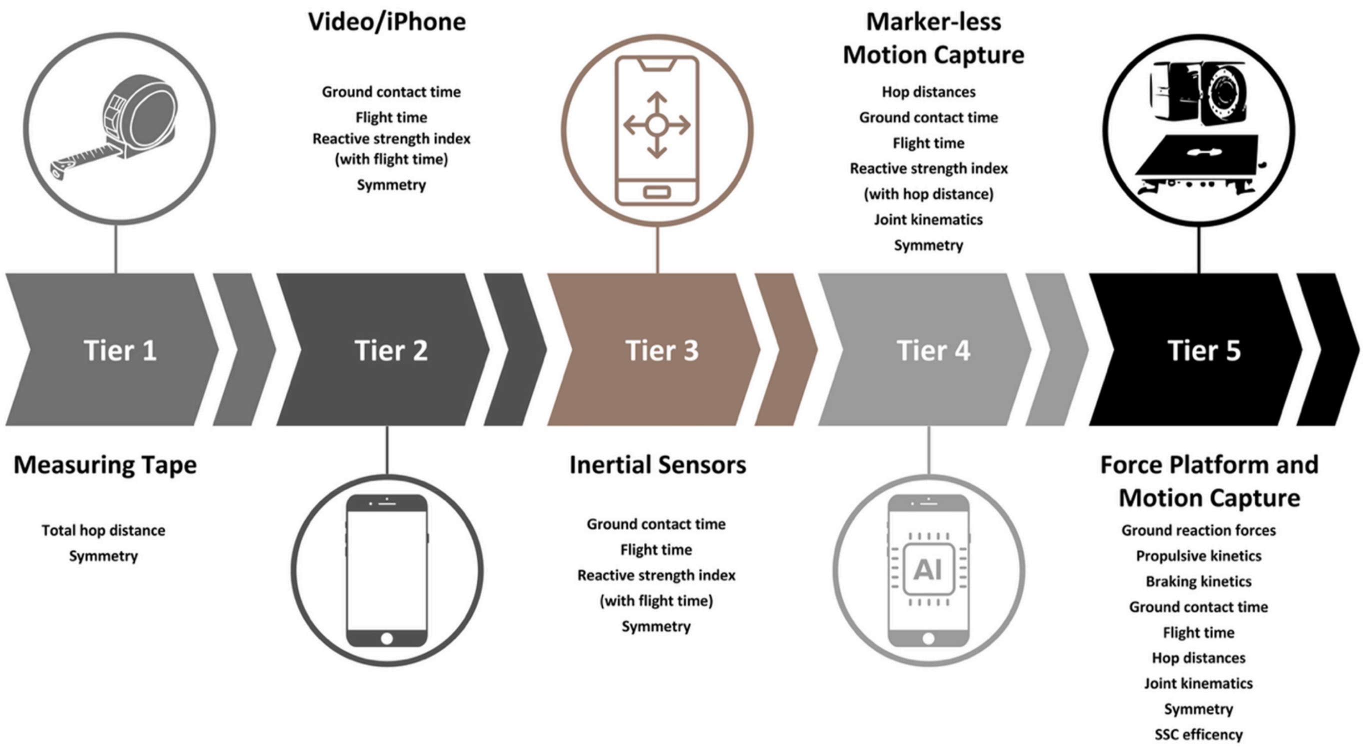


**Fig. 5.** Technological options in the assessment of horizontal multiple hops in series.

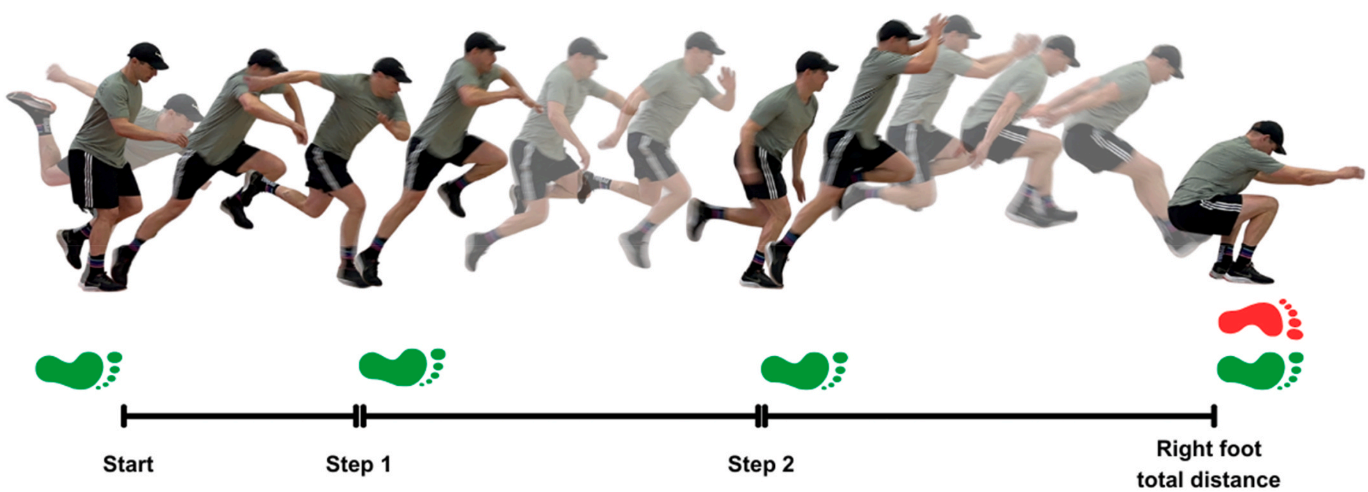


**Fig. 6.** The sequence of a right foot triple hop test (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

when compared to 'gold standard' measurements on force platforms (Comyns et al., 2023). Several commercially available products such as those at Output Sports (https://www.outputsports.com) utilise IMUs capturing data at 500 Hz, and can be easily attached to the dorsal surface of an athlete's training footwear using a Velcro attachment (see Fig. 7) prior to hop assessment, and offer automated measurement of spatio-temporal variables, e.g., ground contact time, flight time, and then reactive strength index (RSI) is derived, as well as proxy measures of landing impact forces based on acceleration data (see Fig. 8). IMUs enable a more nuanced and practical approach to movement assessment in performance and rehabilitation settings. An example of immediate data from a right limb triple hop, collected using an Output Sports IMU and an iPhone is shown in Fig. 8. In this example, key performance metrics including ground contact time (Contact Time), flight time (Air Time), peak acceleration (representing peak deceleration at impact), and reactive strength index (RSI; calculated as Air Time/Contact Time), which are generated from a single triple hop. These variables can be used to assess and monitor changes in both propulsive and braking capabilities over time, as well as to quantify asymmetries between the affected and unaffected limbs. The magnitude of asymmetry from the averaged hop data for the left and right legs is also shown in Fig. 8.

Tier 4 technology offers a more advanced, yet still accessible, solution through the use of 3D marker-less motion analysis systems and integrated Ai based data management, such as VueMotion (https://www.vuemotion.com), which utilise video captured from multiple iPhones. Although further validation is required, preliminary evidence suggests that these systems can provide biomechanical insights comparable to those obtained from traditional marker-based motion capture

**Fig. 7.** Attachment of the IMU sensor to the shoe using a Velcro strap.

technologies, but with significantly reduced cost and complexity (Scataglini et al., 2024; Templin et al., 2024). VueMotion is an AI-driven video analytics platform capable of generating comprehensive kinematic reports, kinograms, and augmented reality overlays, offering deeper insights into the movement strategies employed during each hop. For dual-plane assessment (frontal and sagittal), three iOS devices are required; two for video capture and one to synchronise the recording process. Once footage is collected, it is uploaded to a server, and detailed reports are typically generated within 24 h. These reports include a wide range of outcome variables, and kinematic movement strategy variables across key joints, such as the shoulder, spine, pelvis, knee, and ankle, and at critical time points including initial contact, peak knee flexion, and take-off of triple hops. A small sample of the data is shown in Table 3 and Fig. 9. This information is vital for understanding the motor strategies used by affected versus unaffected limbs and can be leveraged to identify key physical capacities for development, as well as to guide coaching and rehabilitation strategies targeting compensatory gait patterns.

Tier 5 technology incorporates gold-standard biomechanical assessments using both force platforms and motion capture software, limited to laboratory-based data capture. As such, their application to in-field analysis is not practical for most practitioners, and therefore, the discussion of this technology is outside the scope of this article. Future research could, however, employ force platforms to determine stretch-shortening cycle (SSC) efficiency in cyclical movements in the horizontal direction, such as the triple hop, thereby building on the work by Pedley et al. (2022). This could add a further layer to the RTS criteria and drive physical programming, coaching cues, and intent with rehabilitation sessions.

## 5. Conclusion

The triple hop test is a simple, reliable, and effective tool for assessing an athlete's physical status and readiness to return to sport. It can be easily administered with minimal equipment, typically requiring only a tape measure, yet, when combined with accessible and cost-

**Table 3**
A sample of triple hop kinematics data captured using a commercialised AI video application (VueMotion).

| | Left | Right | Asymmetry (%) |
|---|---|---|---|
| Total Distance (m) | 6.77 | 7.23 | 6.36 |
| Hop Distance 1 (m) | 2.08 | 1.92 | 8.33 |
| Hop Distance 2 (m) | 2.00 | 2.25 | 11.11 |
| Hop Distance 3 (m) | 2.69 | 3.06 | 12.09 |
| Reactive Strength Index 1 ($RSI_{horDIST}$) | 6.67 | 8.04 | 17.04 |
| Reactive Strength Index 2 ($RSI_{horDIST}$) | 10.76 | 12.24 | 12.09 |
| Flight Time (%) | 58.65 | 61.31 | 4.34 |
| Ground Contact Time (%) | 41.35 | 38.68 | 6.88 |

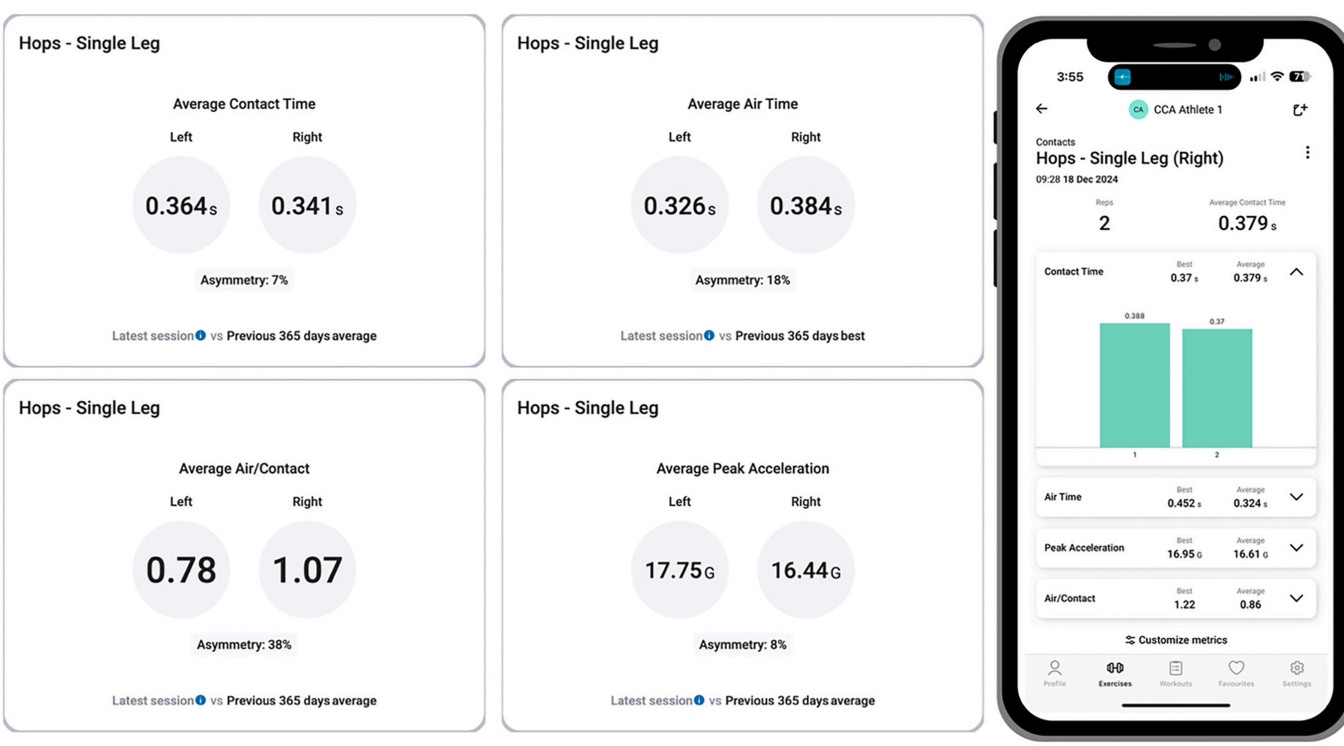


**Fig. 8.** Triple hop kinematics and kinetics are automated using a commercialised inertial measurement unit.

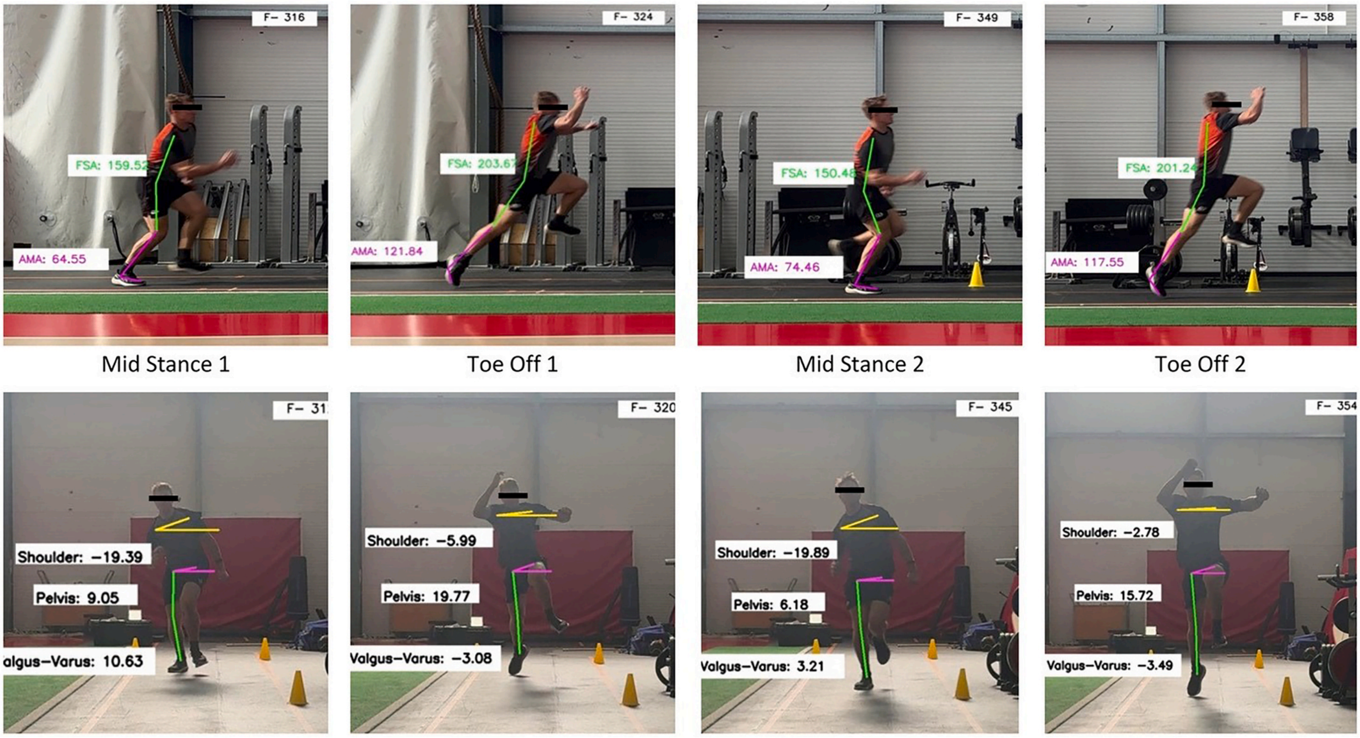


**Fig. 9.** Triple hop joint kinematics automated using a commercialised AI video application (VueMotion) in sagittal and front planes.
**Note:** FSA = femur spine angle; AMA = ankle maximum amortization angle.

effective technology, it can yield higher-level insights into an athlete's neuromuscular and lower limb function. These tools enable asymmetric assessments on nuanced biomechanical components of RTS, providing insight that can inform targeted rehabilitation strategies and guide future programming to optimise recovery while reducing the risk of reinjury.

## CRediT authorship contribution statement

**Anthony P. Sharp:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Jonathon Neville:** Formal analysis, Data curation, Conceptualization. **John B. Cronin:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

## Ethical statement

All data included in this article is from studies conducted in accordance with the guidelines of the Declaration of Helsinki and was approved by the Auckland University of Technology Ethics Committee (17/133 approved November 1, 2018) and the National Institute of Fitness and Sports in Kanoya (8–123 approved January 30, 2018).

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## Declaration of competing interest

The authors declare that there are no commercial, financial, or other relationships that could be construed as a potential conflict of interest with respect to the technology, equipment, or software mentioned in this article. No funding, sponsorship, or affiliation exists between the authors and the companies or products cited.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptsp.2025.09.016.

## References

Alarifi, S. M., Herrington, L. C., Althomali, O. W., Alenezi, F., Bin, S. B., & Jones, R. K. (2025). Biomechanical analysis after anterior cruciate ligament reconstruction at the return-to-sport time point. *Orthopaedic Journal of Sports Medicine, 13*, 1–7.

Ardern, C. L., Glasgow, P., Schneiders, A., Witvrouw, E., Clarsen, B., Cools, A., Gojanovic, B., Griffin, S., Khan, K. M., Moksnes, H., Mutch, S. A., Phillips, N., Reurink, G., Sadler, R., Silbernagel, K. G., Thorborg, K., Wangensteen, A., Wilk, K. E., & Bizzini, M. (2016). Consensus statement on return to sport from the first world congress in sports physical therapy, Bern. *British Journal of Sports Medicine, 50*, 853–864, 2016.

Baez, S., Harkey, M., Birchmeier, T., Triplett, A., Collins, K., & Kuenze, C. (2023). Psychological readiness, injury-related fear, and persistent knee symptoms after anterior cruciate ligament reconstruction. *Journal of Athletic Training, 58*, 998–1003.

Balsalobre-Fernandez, C., Tejero-Gonzalez, C. M., del Campo-Vecino, J., & Bavaresco, N. (2014). The concurrent validity and reliability of a low-cost, high-speed camera-based method for measuring the flight time of vertical jumps. *The Journal of Strength & Conditioning Research, 28*, 528–533.

Barber-Westin, S. D., & Noyes, F. R. (2011). Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: A systematic review. *The Physician and Sportsmedicine, 39*, 100–110.

Bishop, C. (2025). Using ratio data in strength and conditioning: Component parts hold the key. *The Journal of Strength & Conditioning Research, 39*, e176–e179.

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.

Bremner, C. B., Holcomb, W. R., & Brown, C. D. (2015). Knee joint angle influences neuromuscular electrical stimulation-induced torque. *Athletic Training & Sports Health Care, 7*, 165–172.

Buckthorpe, M., Gokeler, A., Herrington, L., Hughes, M., Grassi, A., Wadey, R., Patterson, S., Compagnin, A., La Rosa, G., & Della Villa, F. (2024). Optimising the early-stage rehabilitation process post-acl reconstruction. *Sports Medicine, 54*, 49–72.

Buckthorpe, M., La Rosa, G., & Villa, F. D. (2019). Restoring knee extensor strength after anterior cruciate ligament reconstruction: A clinical commentary. *International Journal of Sports Physical Therapy, 14*, 159–172.

Buckthorpe, M., & Roi, G. S. (2017). The time has come to incorporate a greater focus on rate of force development training in the sports injury rehabilitation process. *Muscles, Ligaments and Tendons Journal, 7*, 435–441.

Cavalcante, J. G. T., Marqueti, R. C., Geremia, J. M., de Sousa Neto, I. V., Baroni, B. M., Silbernagel, K. G., Bottaro, M., Babault, N., & Durigan, J. L. Q. (2021). The effect of quadriceps muscle length on maximum neuromuscular electrical stimulation evoked contraction, muscle architecture, and tendon-aponeurosis stiffness. *Frontiers in Physiology, 12*, Article 633589.

Comyns, T. M., Murphy, J., & O'Leary, D. (2023). Reliability, usefulness, and validity of field-based vertical jump measuring devices. *The Journal of Strength & Conditioning Research, 37*, 1594–1599.

Cooke, R., Rushton, A., Martin, J., Soundy, A., Herrington, L., & Heneghan, N. R. (2025). Lower extremity functional performance tests and their measurement properties in athletes: A systematic review and narrative synthesis. *BMJ Open Sport and Exercise Medicine, 11*, Article e002389.

Cooper, R., & Hughes, M. (2018). The Melbourne Acl rehabilitation guide 2.0. https://team-acl.com/melbourne-acl-rehabilitation-guide.

Creighton, D. W., Shrier, I., Shultz, R., Meeuwisse, W. H., & Matheson, G. O. (2010). Return-to-Play in sport: A decision-based model. *Clinical Journal of Sport Medicine, 20*, 379–385.

Culvenor, A. G., Girdwood, M. A., Juhl, C. B., Patterson, B. E., Haberfield, M. J., Holm, P. M., Bricca, A., Whittaker, J. L., Roos, E. M., & Crossley, K. M. (2022). Rehabilitation after anterior cruciate ligament and meniscal injuries: A best-evidence synthesis of systematic reviews for the optiknee consensus. *British Journal of Sports Medicine, 56*, 1445–1453.

Davey, K., Read, P., Coyne, J., Jarvis, P., Turner, A., Brazier, J., Šarabon, N., Jordan, M. J., & Bishop, C. (2021). An assessment of the hopping strategy and inter-limb asymmetry during the triple hop test: A test–retest pilot study. *Symmetry, 13*, 1890.

dos Reis, A. C., Correa, J. C., Bley, A. S., Rabelo, N. D., Fukuda, T. Y., & Lucareli, P. R. (2015). Kinematic and kinetic analysis of the single-leg triple hop test in women with and without patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy, 45*, 799–807.

Figueroa Poblete, D., Gonzalez Duque, W., Landea Caroca, D., Tapia Castillo, C., & Erskine Ventura, D. (2025). Return-to-Sport tests: Do they reduce risk of Re-Rupture after anterior cruciate ligament reconstruction? *Journal of ISAKOS, 11*, Article 100399.

Fulton, J., Wright, K., Kelly, M., Zebrosky, B., Zanis, M., Drvol, C., & Butler, R. (2014). Injury risk is altered by previous injury: A systematic review of the literature and presentation of causative neuromuscular factors. *International Journal of Sports Physical Therapy, 9*, 583–595.

Gokeler, A., Welling, W., Benjaminse, A., Lemmink, K., Seil, R., & Zaffagnini, S. (2017). A critical analysis of limb symmetry indices of hop tests in athletes after anterior cruciate ligament reconstruction: A case control study. *Orthopaedics and Traumatology: Surgery and Research, 103*, 947–951.

Gokeler, A., Welling, W., Zaffagnini, S., Seil, R., & Padua, D. (2017). Development of a test battery to enhance safe return to sports after anterior cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy, 25*, 192–199.

Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after acl reconstruction: The Delaware-Oslo Acl cohort study. *British Journal of Sports Medicine, 50*, 804–808.

Hovey, S., Wang, H., Judge, L. W., Avedesian, J. M., & Dickin, D. C. (2021). The effect of landing type on kinematics and kinetics during single-leg landings. *Sports Biomechanics, 20*, 543–559.

Jarvis, P., Turner, A., Read, P., & Bishop, C. (2022). Reactive strength index and its associations with measures of physical and sports performance: A systematic review with meta-analysis. *Sports Medicine, 52*, 301–330.

Kotsifaki, R., Korakakis, V., King, E., Barbosa, O., Maree, D., Pantouveris, M., Bjerregaard, A., Luomajoki, J., Wilhelmsen, J., & Whiteley, R. (2023). Aspetar clinical practice guideline on rehabilitation after anterior cruciate ligament reconstruction. *British Journal of Sports Medicine, 57*, 500–514.

Kotsifaki, A., & Whiteley, R. (2023). Criteria-based rehabilitation and return to sport testing after anterior cruciate ligament reconstruction. *Aspetar Sports Medicine Journal, 12*, 60–65.

Kotsifaki, A., Whiteley, R., Van Rossom, S., Korakakis, V., Bahr, R., Sideris, V., Graham-Smith, P., & Jonkers, I. (2022). Single leg hop for distance symmetry masks lower limb biomechanics: Time to discuss hop distance as decision criterion for return to sport after Acl reconstruction? *British Journal of Sports Medicine, 56*, 249–256.

Kyritsis, P., Bahr, R., Landreau, P., Miladi, R., & Witvrouw, E. (2016). Likelihood of Acl graft rupture: Not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *British Journal of Sports Medicine, 50*, 946–951.

Lloyd, R. S., Oliver, J. L., Kember, L. S., Myer, G. D., & Read, P. J. (2020). Individual hop analysis and reactive strength ratios provide better discrimination of Acl reconstructed limb deficits than triple hop for distance scores in athletes returning to sport. *The Knee, 27*, 1357–1364.

Losciale, J. M., Zdeb, R. M., Ledbetter, L., Reiman, M. P., & Sell, T. C. (2019). The association between passing return-to-sport criteria and second anterior cruciate ligament injury risk: A systematic review with meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy, 49*, 43–54.

Macdonald, B., McAleer, S., Kelly, S., Chakraverty, R., Johnston, M., & Pollock, N. (2019). Hamstring rehabilitation in elite track and field athletes: Applying the British athletics muscle injury classification in clinical practice. *British Journal of Sports Medicine, 53*, 1464–1473.

Munro, A. G., & Herrington, L. C. (2011). Between-session reliability of four hop tests and the agility T-Test. *The Journal of Strength & Conditioning Research, 25*, 1470–1477.

Noyes, F. R., Barber, S. D., & Mangine, R. E. (1991). Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *The American Journal of Sports Medicine, 19*, 513–518.

Pedley, J. S., Lloyd, R. S., Read, P. J., Moore, I. S., Myer, G. D., & Oliver, J. L. (2022). A novel method to categorize stretch-shortening cycle performance across maturity in youth soccer players. *The Journal of Strength & Conditioning Research, 36*, 2573–2580.

Raoul, T., Klouche, S., Guerrier, B., El-Hariri, B., Herman, S., Gerometta, A., Lefevre, N., & Bohu, Y. (2019). Are athletes able to resume sport at six-month mean Follow-up after anterior cruciate ligament reconstruction? Prospective functional and psychological assessment from the French anterior cruciate ligament study (Fast) cohort. *The Knee, 26*, 155–164.

Sarabon, N., Kozinc, Z., & Bishop, C. (2023). Comparison of vertical and horizontal reactive strength index variants and association with change of direction performance. *The Journal of Strength & Conditioning Research, 37*, 84–90.

Šarabon, N., Milinović, I., Dolenec, A., Kozinc, Ž., & Babić, V. (2022). The reactive strength index in unilateral hopping for distance and its relationship to sprinting performance: How many hops are enough for a comprehensive evaluation? *Applied Sciences, 12*, Article 11383.

Scataglini, S., Abts, E., Van Bocxlaer, C., Van den Bussche, M., Meletani, S., & Truijen, S. (2024). Accuracy, validity, and reliability of markerless camera-based 3d motion capture systems versus marker-based 3d motion capture systems in gait analysis: A systematic review and meta-analysis. *Sensors, 24*, 3686.

Scott, W., Adams, C., Fisher, J., Fisher, S., Jones, K., & Mathieu, B. (2021). Electrically elicited quadriceps muscle torque: Comparison at three knee angles. *Physiotherapy Theory and Practice, 37*, 729–735.

Sharp, A., Cronin, J., Neville, J., Diewald, S., Stolberg, M., Draper, N., & Walter, S. (2023). Comparison of multiple hop test kinematics between force-platforms and video footage – A cross sectional study. *International Journal of Kinesiology & Sports Science, 11*, 23–28.

Sharp, A. P., Neville, J., Diewald, S. N., Oranchuk, D. J., & Cronin, J. B. (2024). Videographic variability of triple and quintuple horizontal hop performance. *Journal of Sport Rehabilitation, 33*, 570–581.

Sharp, A., Neville, J., Nagahara, R., Wada, T., & Cronin, J. (2025a). Do outcome or movement strategy variables provide better insights into asymmetries during multiple-hops? *Biomechanics, 5: 67*.

Sharp, A., Neville, J., Nagahara, R., Wada, T., & Cronin, J. (2025b). Using multiple-hop assessments and reactive strength indices to differentiate sprinting performance in sportsmen. *Applied Sciences, 15*, 1685.

Sharp, A. P., Neville, J., Nagahara, R., Wada, T., & Cronin, J. B. (2025c). *Stretch-load demands in multiple hops: Implications for athletic performance and rehabilitation* (submitted for publication).

Shrier, I. (2015). Strategic assessment of risk and risk tolerance (Starrt) framework for return-to-play decision-making. *British Journal of Sports Medicine, 49*, 1311.

Sousa, P. L., Krych, A. J., Cates, R. A., Levy, B. A., Stuart, M. J., & Dahm, D. L. (2017). Return to sport: Does excellent 6-Month strength and function following Acl reconstruction predict midterm outcomes? *Knee Surgery, Sports Traumatology, Arthroscopy, 25*, 1356–1363.

Templin, T., Riehm, C. D., Eliason, T., Hulburt, T. C., Kwak, S. T., Medjaouri, O., Chambers, D., Anand, M., Saylor, K., Myer, G. D., & Nicolella, D. P. (2024). Evaluation of drop vertical jump kinematics and kinetics using 3d markerless motion capture in a large cohort. *Frontiers in Bioengineering and Biotechnology, 12*, Article 1426677.

van der Horst, N., Backx, F., Goedhart, E. A., Huisstede, B. M., & Group, H. I.-D. (2017). Return to play after hamstring injuries in football (Soccer): A worldwide Delphi procedure regarding definition, medical criteria and decision-making. *British Journal of Sports Medicine, 51*, 1583–1591.

Webster, K. E., & Feller, J. A. (2019). Clinical tests can be used to screen for second anterior cruciate ligament injury in younger patients who return to sport. *Orthopaedic Journal of Sports Medicine, 7*, Article 2325967119863003.

Wellsandt, E., Failla, M. J., & Snyder-Mackler, L. (2017). Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. *Journal of Orthopaedic & Sports Physical Therapy, 47*, 334–338.

White, M. S., Horton, W. Z., Burland, J. P., Seeley, M. K., & Lepley, L. K. (2021). The utility of functional data analyses to reveal between-limbs asymmetries in those with a history of anterior cruciate ligament reconstruction. *Journal of Athletic Training, 56*, 272–279.

Zarro, M., Dickman, M., Hulett, T., Rowland, R., Larkins, D., Taylor, J., & Nelson, C. (2023). Hop to it! the relationship between hop tests and the anterior cruciate ligament – return to sport index after anterior cruciate ligament reconstruction in ncaa division 1 collegiate athletes. *International Journal of Sports Physical Therapy, 18*, 1076–1084.

Zhou, W., Liu, X., Hong, Q., Wang, J., & Luo, X. (2024). Association between passing return-to-sport testing and Re-Injury risk in patients after anterior cruciate ligament reconstruction surgery: A systematic review and meta-analysis. *PeerJ, 12*, Article e17279.