ASSESSING VERTICAL JUMP FORCE-TIME ASYMMETRIES IN ATHLETES WITH ANTERIOR CRUCIATE LIGAMENT INJURY

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INTRODUCTION

An anterior cruciate ligament (ACL) rupture is a devastating injury for an athlete. ACL injuries occur frequently in field sports[1–5] and winter slope sports, such as alpine ski racing and snowboarding[6–9]. After suffering an ACL rupture, reconstruction surgery (ACLR) is often recommended for athletes to restore knee joint stability, but functional deficits are likely to persist after surgery[10]. While a high fraction of winter slope sport athletes have been shown to return to their preinjury performance level after ACLR[11], less than 65% of field sport athletes return to the same level of competitive performance[12–14]. The risk of ACL injury in athletes with a previous history of ACLR is substantially greater compared to athletes with no history of ACL injury[15], and ACL reinjuries, especially on the contralateral limb, are prevalent in winter slope sports[16] and field sports[1,4,15] alike. Despite an elevated risk for reinjury, elite athletes with ACLR often return to sport with pronounced functional deficits, such as elevated between-limb (interlimb) asymmetries in muscle strength and power[17–22], and sport science/sport medicine practitioners have been shown to rely only on subjective assessments and time-since-surgery as determinants of return to sport readiness[23].

To account for the high risk of ACL reinjury, objective testing that uses a functional milestone based approach is recommended prior to return to sport clearance[24] alongside ensuring adequate time for tissue healing[25]. However, the efficacy of functional return to sport testing batteries has been questioned recently due to the high fraction of athletes who pass criteria while masking deficits that are associated with ACL reinjury (e.g. achieving a limb symmetry index > 90% in a single leg hop test for distance but failing to achieve a quadriceps strength limb symmetry index > 90%)[18,26]. It is likely that individuals with a history of ACLR compensate during performance-based functional testing by altering their movement strategies. For example, they may rely on a hip dominant jump or squat movement pattern to account for persistent neuromuscular deficits such as knee extensor strength loss[27].

The requirement for practical and sensitive assessments that can be used in a high-performance sport environment to detect deficits in athletes following ACLR has spurred practitioners to incorporate field-based assessments of vertical jump interlimb force-time asymmetries measured with a dual force plate system[19,20,22,28–33]. While there are currently no studies providing evidence of a statistical relationship between elevated lower limb vertical jump force-time asymmetries and an increased risk ACL reinjury, assessing vertical jump asymmetries is becoming increasingly popular. The aim of this short review is to provide a practitioner's perspective on assessing lower limb force-time asymmetries in the vertical jump using a dual force plate system. We will focus on strategies to enhance data quality, force-time analysis techniques, normative values for vertical jump force-time asymmetries, considerations for employing asymmetry testing with athletes following ACLR, and future perspectives.

THE BASICS OF FORCE-TIME ANALYSIS

Newton's second law of motion tells us that the acceleration of an object with a constant mass in any given direction is proportional to the net forces that are applied to the object in that same direction. This equation also connects the application of force in a given time frame (i.e. impulse) to an object's change in velocity. These equations are shown below to determine the takeoff velocity in a vertical jump (Figure 1). The relevance of these equations is that the application of force during human movements like the vertical jump dictates how fast we move.

The vertical velocity of the body centre of mass can also be determined by time integration of the vertical component of the ground reaction force, Fz[37], and double integration of the acceleration vs. time tracing allows us to determine the displacement of the body centre of mass (Figure 2). The derivation of these equations is shown in Figure 2 and they are helpful when assessing vertical jump asymmetries in ACLR athletes. Whereas lower limb strength asymmetries are often assessed using discrete time point analysis (e.g. the instant of peak force or peak torque in a maximum voluntary contraction), vertical jump force-time asymmetries are best assessed over movement phases of interest and multiple movement cycles[38]. Movement phases can be defined using the velocity of the body centre of mass show in Figure 2A and 2C[20–22,28,30,32]. In addition to the method described here whereby the movement phases of interest in the vertical jump are defined using the velocity of the body centre of mass, other statistical methods, such as functional data analysis[28] and statistical parametric mapping, can be used to quantify interlimb asymmetries across the vertical jump force-time waveform.

It is important to evaluate interlimb asymmetries over the entire vertical jump force-time curve. Figure 3 shows the countermovement jump (CMJ) and squat jump (SJ) force-time asymmetries for an athlete with a history of ACLR. Limb dominance indicating greater force production on the reconstructed limb is shown with the light shaded blue region and non-injured limb dominance is shown

1

Newton's Second Law → $\bar{F} = m\bar{a}$

$$\bar{F} = m\,\frac{d\bar{v}}{dt}$$

$$\int \bar{F}dt = m(\bar{v}_{final} - \bar{v}_{initial})\text{, where } \bar{v}_{initial} = 0$$

impulse Momentum Relationship → $\int \frac{\bar{F}dt}{m} = \bar{v}_{final} = Takeoff\ Velocity$

Figure 1: Determining the takeoff velocity in the vertical jump using the impulse momentum relationship.

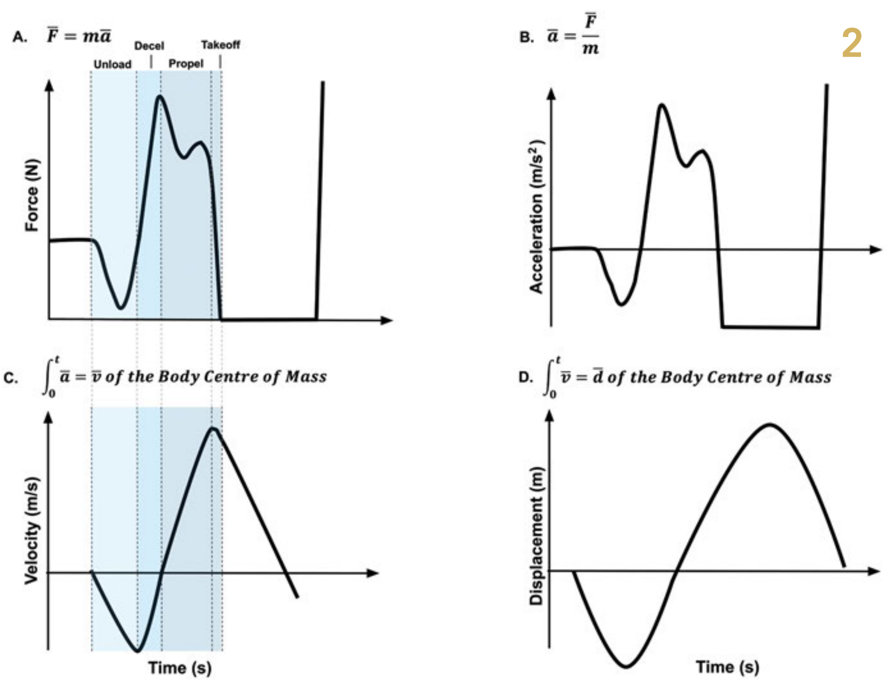

Figure 2: Sequence of equations for using time integration of the vertical ground reaction force – $\bar{F}$ (A) to determine the acceleration – $\bar{a}$ (B), velocity – $\bar{v}$ (C) and displacement – $\bar{d}$ (D) of the body centre of mass.

with a dark blue shade. Visual inspection of Figure 3 shows that the directionality of the interlimb asymmetry changes over the propulsive and landing phases of the CMJ and SJ, with the ACLR limb generating a higher impulse in the CMJ eccentric deceleration phase and the early phase of the SJ. While this may appear counterintuitive, greater loading of the ACLR limb in the vertical jump has been reported elsewhere[20,21]. Conversely, the non-injured limb is dominant in the concentric (propulsive) phase of the CMJ and the late takeoff phase of the SJ.

The *movement asymmetry* shown in Figure 3 differs from strength or power interlimb asymmetries measured using dynamometry. In fact, humans display considerably more variability when it comes to movement asymmetries[39], and interlimb differences appear to be task dependent[40]. In the ACLR athlete factors such as the graft type can affect the directionality of vertical jump interlimb asymmetries[32] alongside propulsive versus energy absorptive movements[21]. For example, patients undergoing a semitendinosus autograft have been shown to demonstrate lower CMJ eccentric deceleration phase and concentric phase asymmetry compared to patients with a bone patellar tendon bone autograft[32].

In summary, we can improve our detection of vertical jump force-time interlimb asymmetries in athletes with ACLR using the following steps:

- Apply the physics of motion when assessing vertical jump force-time asymmetries.
- Assess vertical jump interlimb asymmetries over the entire force-time tracing and phases of movement.
- Assess vertical jump interlimb asymmetries over multiple movement cycles. Avoid discrete time point analysis such as the instant of the peak vertical ground reaction force.
- Remember that interlimb asymmetries are often variable and specific to the task in which they are measured.
- The directionality of the interlimb asymmetry may change in the recovering ACLR athlete; thus, both the magnitude and direction of between-limb differences should be considered
- Interlimb asymmetries in ACLR athletes are also affected by factors like the surgical procedure.

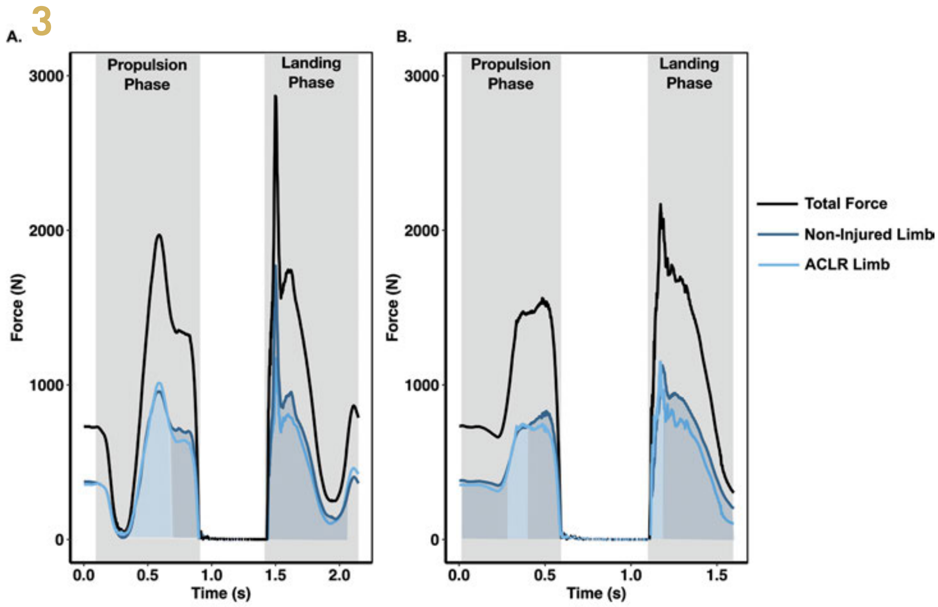

Figure 3: Vertical jump force-time interlimb asymmetries for an athlete with anterior cruciate ligament reconstruction (ACLR) during a countermovement jump (A) and squat jump (B). The light blue shading shows ACLR limb dominance and the dark blue shading shows non-injured limb dominance.

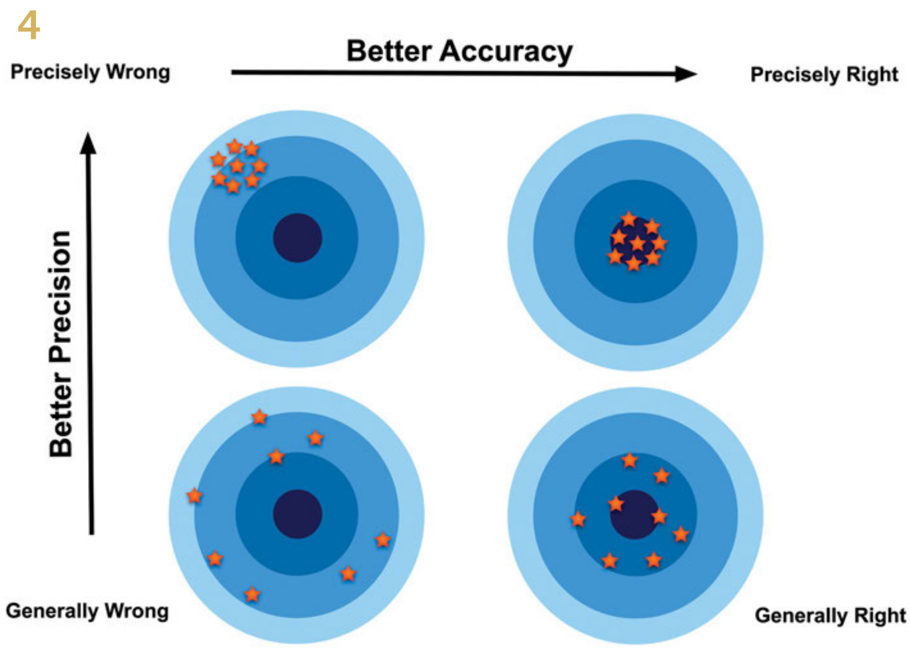

Figure 4: An analogy for accuracy and precision.

GETTING QUALITY DATA

Some degree of error is present in any measurement system. A dual force plate system doubles the measurement error and a faulty force plate (or two) can be problematic. For example, imagine we are assessing an athlete recovering from a right limb ACLR whose true interlimb asymmetry index is 20%. If the right force plate increases the vertical ground reaction force (Fz) and the left force plate decreases Fz, we may observe an asymmetry index of 9% and underestimate the true imbalance. We would erroneously conclude the athlete is sufficiently prepared for a return to sport. This example highlights the importance of ensuring data quality, especially given the impact on athlete health and safety. To

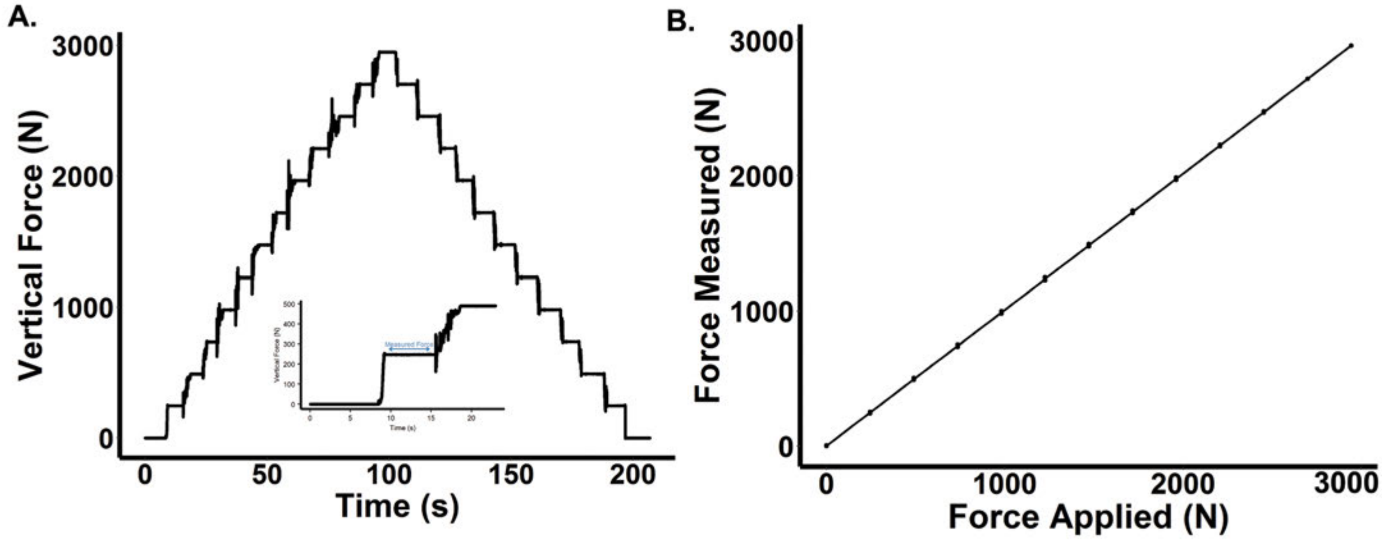

Figure 5: An example calibration procedure showing a stepwise external load application to a force plate (A). Assessment of the linear relationship between the applied force and measured force (B).

further illustrate this point, we can view the accuracy and precision of our testing instruments like a dart board (Figure 4).

The accuracy and precision of a force plate may change over time. This may be due to normal wear and tear, sensor damage and even changing the physical environment where the force plate is used (e.g. moving a portable force plate from a low traffic laboratory to a busy weight room). The best safeguard for ensuring the accuracy and precision of a force plate is routine calibration procedures that tests the force plate across the operating range. A simple calibration procedure is depicted in Figure 5A. In this example, an external load is applied in 25 kg increments up to a total of 300 kg. The linearity of the measured force versus the applied force is then assessed (Figure 5B). Importantly, the same external load should be used in each calibration session. The frequency of calibration depends on how much data we are willing to lose. Suppose we perform two calibrations separated by 6 months and detect a faulty force plate in the second session. We are justified to question all the data that was collected between the two calibration sessions.

Whether or not this is a problem depends on the practitioner and the scenario. For example, data that is collected for scientific purposes may require more frequent calibrations compared to data that is collected for the purpose of providing biofeedback to the athlete.

Force plate calibration may seem trivial or unnecessary; however, consider the

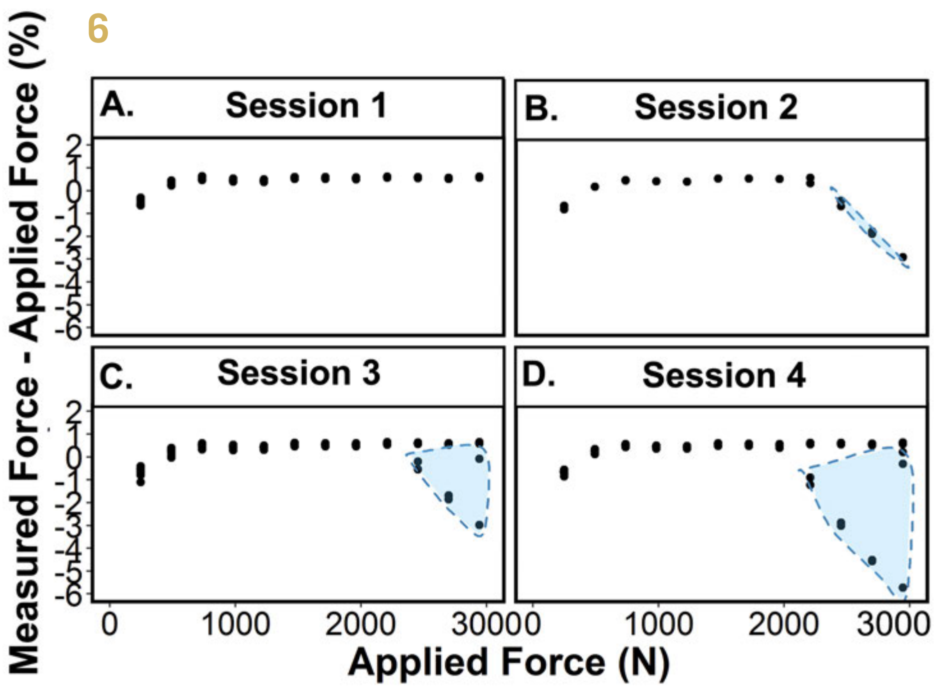

Figure 6: Routine calibration sessions to detect a malfunctioning force plate. The error observed in Sessions 3 and 4 can be easily mistaken for a physiological change or a recovery in interlimb asymmetry for an ACLR athlete.

example provided in Figure 6 that depicts four routine calibration sessions of a Pasco force plate, a brand that is often used in high performance sport settings because of the low cost and portability. Panel 6A indicates the accuracy of a Pasco force plate is sufficient for use in high performance sport, a finding consistent with other reports[34]. However, a progressive loss in accuracy is seen between the first calibration session and the three subsequent sessions. By the third session, forces that are typically measured in a vertical jump (≈ 2000 N) are impacted. Problematically, the loss of accuracy (3-5%) is consistent with what a practitioner might expect in terms of a physiological change in an elite athlete or a functional change that might occur with an ACLR athlete throughout rehabilitation.

The impact of failing to detect a faulty force plate is illustrated in Figure 7. Measurement error increases with the fast

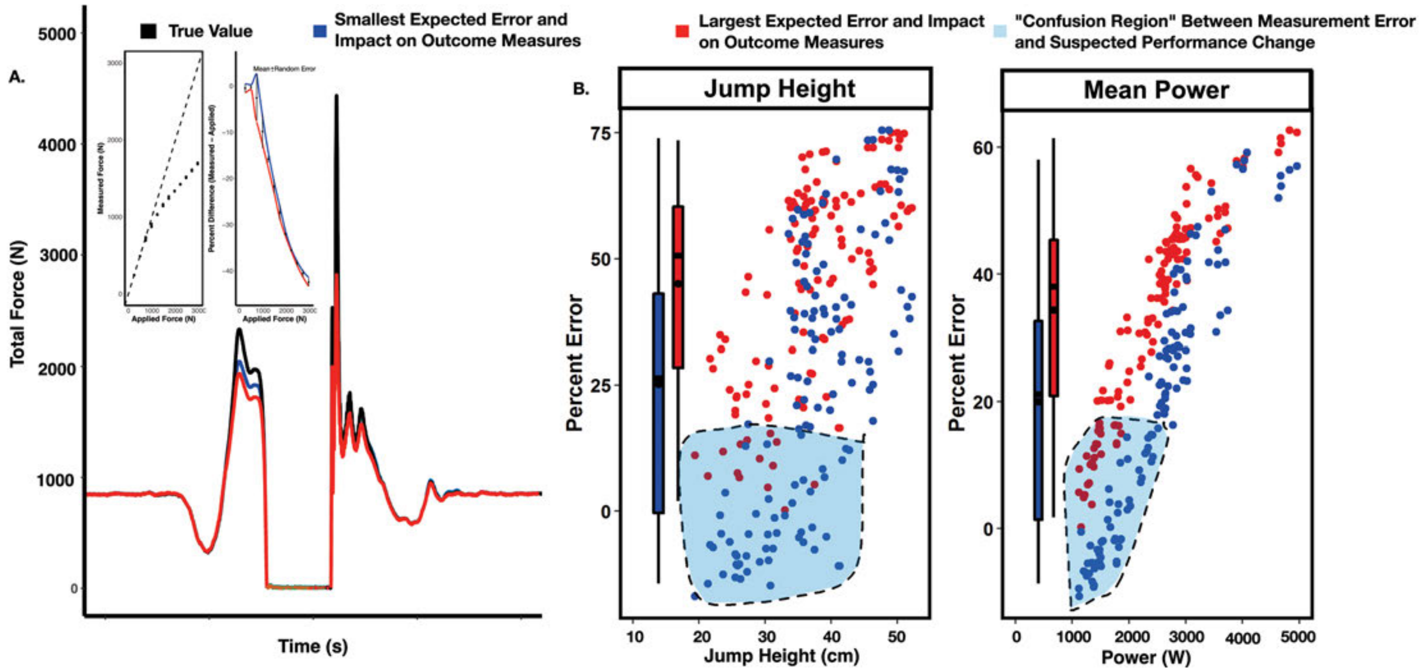

Figure 7: Consequences of a malfunctioning force plate on vertical jump force-time variables are shown. We established the measurement error of a faulty force plate (Panel 4A - inset). The lower and upper limits of agreement were used to adjust force-time curves in order to establish a 'best case' and 'worst case' scenario, had jumps been measured using the malfunctioning force plate (Panel 4A - main). Force-time analysis (see section below) was conducted for 'true', 'best case', and 'worst case' scenarios using 635 representative vertical jumps. The percent error from 'true' was calculated for common vertical jump outcome measures (Panel 4B). Note the overlap between the expected error as a result of equipment malfunction, and changes that could be expected from training (0-20%) shown in the shaded blue region. This highlights the potential for type I and type II training errors if equipment calibration is not performed (i.e. mistaking a performance change for measurement error or missing a performance change due to measurement error).

application of force, like in a vertical jump or when assessing rate of force development (RFD). The loss of accuracy of the force plate could be easily mistaken for typical performance changes in jump height and mechanical power (Figure 7B and 7C), or a functional change in vertical jump force-time asymmetry.

We have found that hard landings on the corner of a portable force plate will exceed the load cell capacity, accelerating the loss of accuracy. To mitigate this problem, a practitioner might decide to use a force plate with a higher load capacity. However, there is a tradeoff between the capacity of a load cell and its accuracy at the low and high end of its operating range. While a force plate with > 2000 kg load capacity can withstand a high force jump landing, the accuracy of the plate may be less than ideal when measuring forces associated with jumping and squatting movements.

Cumulatively, we can improve our data quality processes when assessing interlimb asymmetries with dual force plate systems using a few simple steps:

- Purchase a force plate carefully. Consider the types of movements and tests that will be performed on the force plate. Ask the supplier about the accuracy and precision of the force plate across its operating range. Consider the force plates load capacity and required accuracy for the types of testing that will be performed.
- Calibrate force plates regularly across the operating range. Pay close attention to non-linearities between the measured force and applied force. The calibration frequency depends on the purpose (e.g. biofeedback vs. scientific research), the amount of data we are willing to lose in the event a faulty force plate is detected, the force plate brand/durability, and the testing environment.
- If possible, compare the new force plate to an existing system. Assess the test-retest reliability of specific jump protocols using a new force plate, and ensure it is consistent with previously collected data and what is reported in the scientific literature.
- As vertical jump force-time analysis involves mathematical calculations like time integration, it is important to accurately determine the athlete's body weight with a quiet standing period that is obtained for each vertical jump force-time recording[35]. Choose a sampling frequency of at least 500 Hz especially if more detailed vertical jump force-time analysis is planned[36].

NORMATIVE ASYMMETRY DATA

Normative vertical jump asymmetry data is shown in Figure 8, obtained from 96 competitive alpine ski racers (ACLR: n=23). These athletes collectively performed 1030 CMJ tests and 629 SJ tests over a 9-year time period on a dual force plate system during routine athlete monitoring, lower body strength testing, and throughout the post-surgical period after ACLR. A 5-jump mean asymmetry index was calculated for each jump test between 4 months and more than 5 years post-surgery. Athletes with other lower extremity injuries including leg fractures, tendinopathies, osteochondral disease, meniscal tears, and knee collateral ligament sprains were excluded along with those who reported acutely symptomatic lumbar spine injuries. The interlimb asymmetry index was calculated for specific phases of the CMJ including the eccentric

The interlimb asymmetry index (AI)

$$AI\ Non-Injured\ Athletes = \left(\frac{Right\ Limb\ Impulse - Left\ Limb\ Impulse}{Maximum\ of\ Left\ and\ Right\ Impulse}\right) * 100$$

$$AI\ ACLR\ Athletes = \left(\frac{Contralateral\ Limb\ Impulse - ACLR\ Limb\ Impulse}{Maximum\ of\ Left\ and\ Right\ Impulse}\right) * 100$$

deceleration, concentric and landing phases, and the SJ early takeoff, late takeoff and landing phases using the formulae above and according to the procedures described elsewhere[20–22]:

Using this formula, a positive value for non-injured control athletes indicates right limb dominance and a negative value shows left limb dominance. For ACLR athletes, a positive value reflects non-injured limb dominance whereas a negative value designates ACLR limb dominance. The data shown in Figure 8 is specific to alpine ski racers, but alpine ski racers perform bidirectional turns in training and racing, suggesting that there are no sport-specific requirements for a dominant limb.

A summary of the median and range for phase-specific asymmetries is provided in Table 1. ACLR athletes demonstrated a higher asymmetry index for the concentric phase of the CMJ and late takeoff phase of the SJ, which is consistent with other reports[20,22,33].

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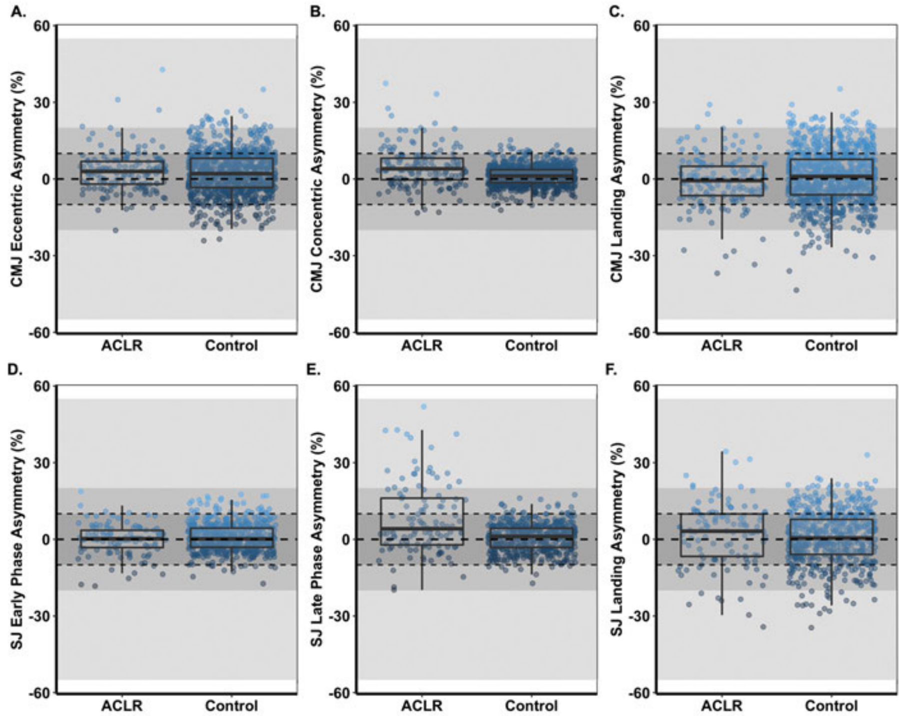

Figure 8: Vertical jump interlimb asymmetries for ACLR (n=23) and non-injured competitive alpine skiers (n=73) for the countermovement jump (CMJ) eccentric deceleration phase (A), CMJ concentric phase (B), CMJ landing phase (C), squat jump (SJ) early takeoff phase (D), SJ late takeoff phase (E) and SJ landing phase (F). The dark grey band represents an asymmetry index of ± 10% and the light grey band represents an asymmetry index of ±20%.

Table 1

	CMJ Eccentric Phase Asymmetry (%)			*CMJ Concentric Phase Asymmetry (%)*			*CMJ Landing Phase Asymmetry (%)*		
	Min	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*
ACLR	-20.1	42.8	3.0	-13.3	37.4	4.0	-36.9	29.1	-0.6
Control	-24.2	35.0	2.1	-12.2	15.3	1.2	-43.5	35.3	1.0
	SJ Early Takeoff Phase Asymmetry (%)			*SJ Late Takeoff Phase Asymmetry (%)*			*SJ Landing Phase Asymmetry (%)*		
	Min	*Max*	*Median*	*Min*	*Max*	*Median*	*Min*	*Max*	*Median*
ACLR	-18.3	18.7	0.2	-19.8	51.9	4.1	-34.3	34.4	3.2
Control	-17.4	17.6	0.2	-17.2	17.4	1.1	-34.6	33.0	0.5

Table 1: Summary of the median, minimum and maximum asymmetry indices for the squat jump (SJ) and countermovement jump (CMJ) in anterior cruciate ligament reconstructed (ACLR) and non-injured (control) competitive alpine skiers.

Landing asymmetries were variable for both groups. The non-injured athletes displayed greater variability in the eccentric deceleration phase of the CMJ compared to the concentric phase of the CMJ, and the majority of non-injured athletes displayed an interlimb asymmetry index less than 10% over the jump tests, which is similar to other reports (Figure 9)[32].

The relationship between elevated vertical jump asymmetries and risk for lower body injury is unknown. However, we may be able to develop some simple heuristics using the normative data presented in Table 1 and in Figure 9 to improve the training process. Injury prediction is challenging but sport science and sport medicine practitioners are often seeking to identify trainable deficits that either lead to a performance improvement or mitigate a perceived injury risk factor. For example, suppose we observed a 50% asymmetry in a non-injured athlete. This value is extreme and highly atypical. The new information would allow us to adjust our decision making, particularly around exercise prescription and training program design to reduce the interlimb asymmetry.

Let's consider a real-world example shown below in Figure 10. Vertical jump asymmetry testing was conducted with 66 competitive athletes prior to the start of the competitive season (baseline). Athletes performed 5 CMJs and 5 SJs but only the CMJ data are shown. The occurrence of knee injuries was tracked in a prospective manner. No training decisions were made from the baseline test results. Suppose we chose a cutoff of > 20% asymmetry to flag an athlete requiring our attention. This heuristic would capture half of the athletes who eventually go on to suffer a knee injury and none of the non-injured athletes. Notably, four athletes who went on to suffer a knee injury presented with an eccentric deceleration asymmetry greater than 20%.

Using the normative data shown above in Figures 8 and 9, we can further contextualize the chance of observing an eccentric deceleration asymmetry greater than 20% in a group of non-injured athletes. Of the 876 CMJ tests performed by the non-injured alpine skiers, only 2.7% of the asymmetry scores were greater than 20%. We can summarize our section on normative vertical jump asymmetry testing data with the following bullet points:

- ACLR athletes present with higher vertical jump force-time interlimb asymmetry in the late takeoff phase of the SJ and the concentric phase of the CMJ compared to non-injured athletes.
- Non-injured athletes typically present with vertical jump interlimb asymmetries less than 10%.
- Based on our real-world training example, if we used a cut-off of 20% to indicate an atypical asymmetry score for a non-injured athlete, we would have only captured athletes who went on to suffer a knee injury. Further, an eccentric deceleration asymmetry > 20% occurs infrequently, and may provide us with new information on which we can base training program design and exercise prescription decisions.

9

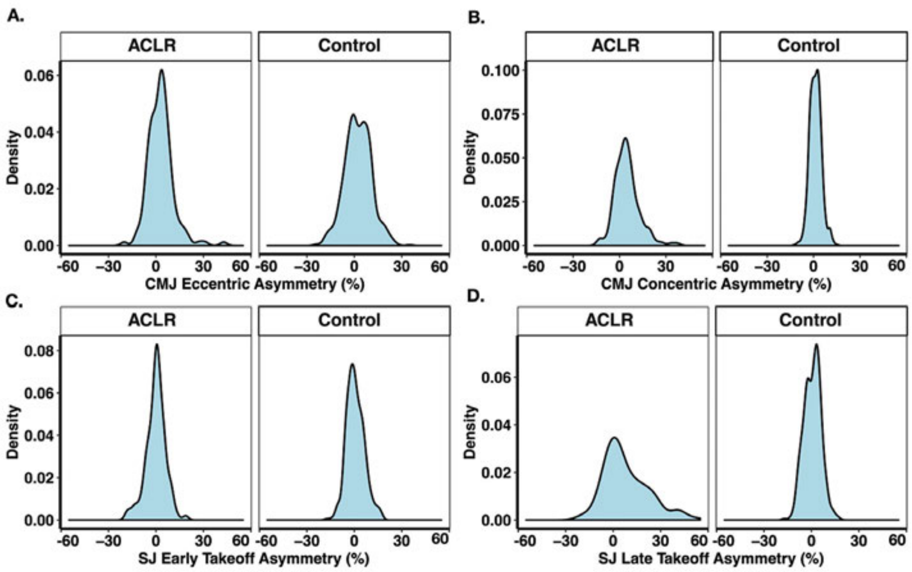

Figure 9: Vertical jump interlimb asymmetries density plots representing the distribution of the asymmetry indices for the countermovement jump (CMJ) eccentric deceleration phase (A), CMJ concentric phase, squat jump (SJ) early takeoff phase (C), SJ late takeoff phase (D).

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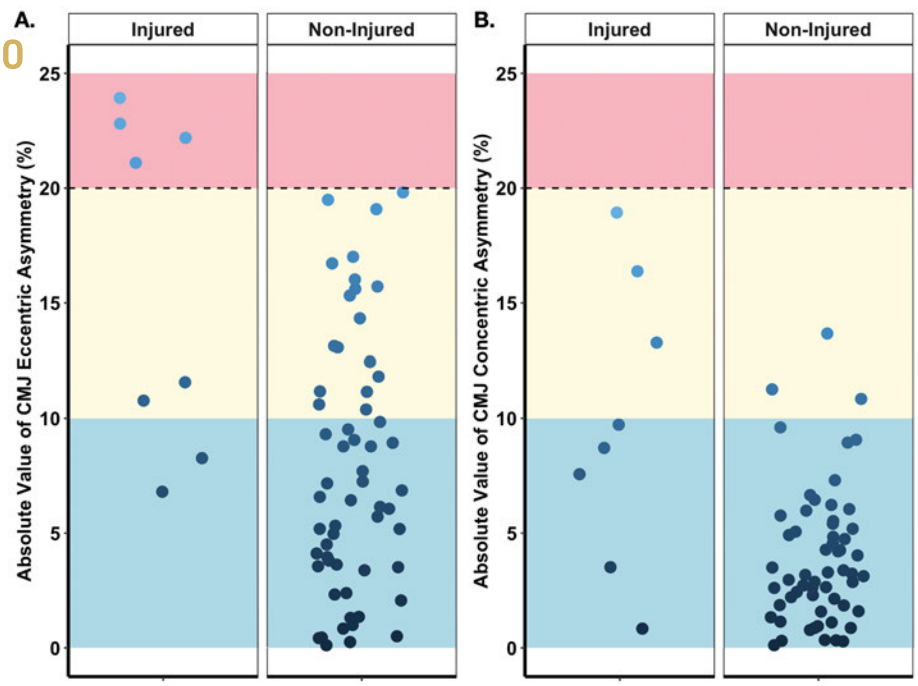

Figure 10: Prospective data from 66 competitive athletes undergoing countermovement jump (CMJ) interlimb asymmetry testing at the start of the pre-competitive training period. Injury surveillance was conducted to track knee injuries. A cut-off threshold of an eccentric asymmetry > 20% captured 50% of the injured athletes and none of the non-injured controls. Panel A shows the CMJ eccentric deceleration phase asymmetry and Panel B shows the CMJ concentric phase asymmetry.

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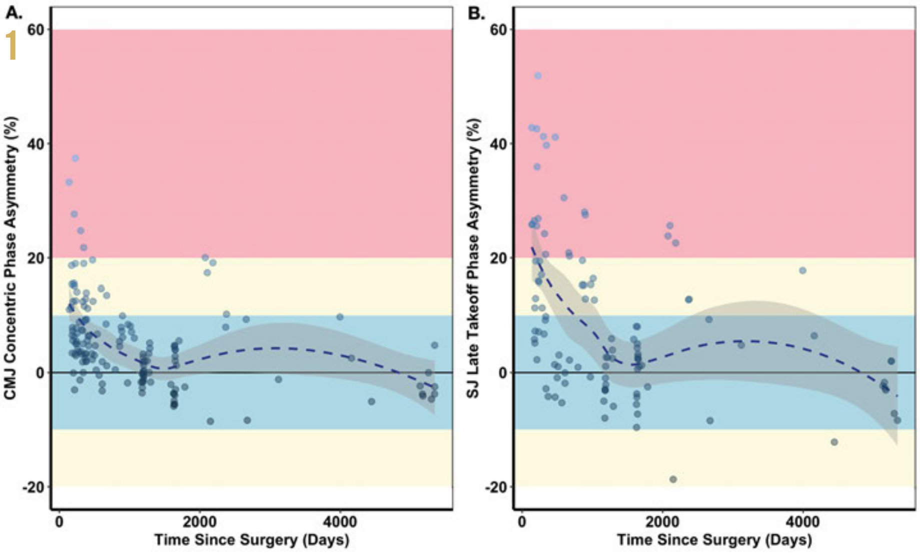

Figure 11: Time-course recovery of countermovement jump (CMJ) and squat jump (SJ) interlimb asymmetries in competitive alpine skiers after anterior cruciate ligament reconstruction (ACLR) surgery. Panel A depicts the CMJ concentric phase asymmetry and Panel B shows the SJ late takeoff phase asymmetry.

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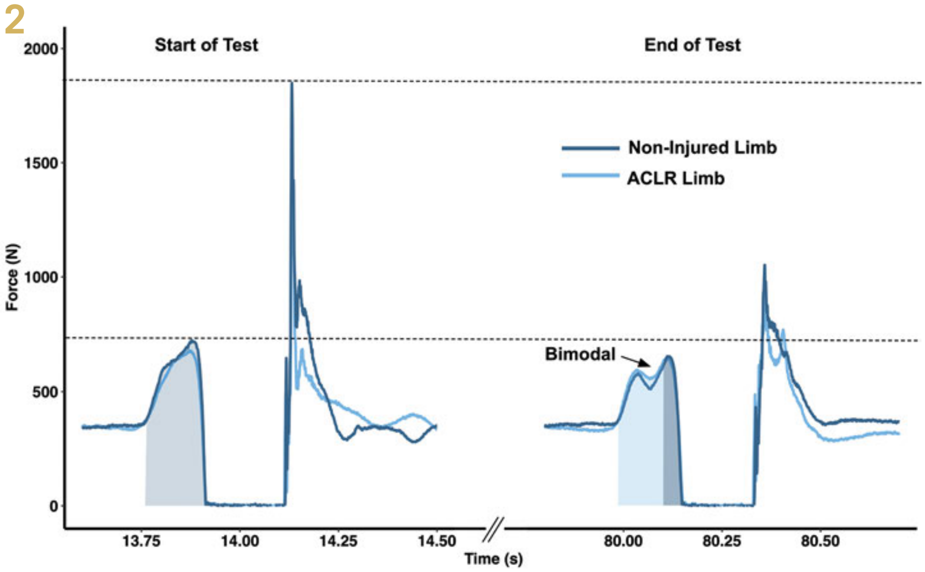

Figure 12: An 80-second repeated squat jump (SJ) test force-time curves obtained from a competitive alpine skier with anterior cruciate ligament reconstruction (ACLR) surgery. The athlete becomes more symmetrical in the late takeoff phase at the end of the test and the force-time curve becomes bimodal. Black dashed lines show a reduction in the vertical ground reaction force for the propulsion and landing phases of the SJ.

- While injury prediction is inherently challenging, simple heuristics and data-informed decision making using vertical jump asymmetry testing can assist sport science and sport medicine practitioners to identify trainable deficits in non-injured and injured athletes.

VERTICAL JUMP FORCE-TIME ASYMMETRIES IN ATHLETES WITH ACLR

Standardized and repeatable neuromuscular assessments are important for athletes returning to sport after ACLR[10,16,18,19,23]. While there is evidence supporting the use of long-standing assessments like quadriceps strength testing[18], the predictive validity of functional performance tests like the single leg hop for distance are equivocal[26]. It may be the case that ACLR athletes compensate during performance-based testing to achieve benchmarks while masking deficits[27]. In addition to the performance outcomes obtained from vertical jump testing such as jump height and mechanical power, we can also assess how an athlete achieved performance outcomes by analyzing the CMJ and SJ force-time recording as described above.

In individuals with ACLR, CMJ concentric phase force-time interlimb asymmetries are associated with knee extensor strength interlimb asymmetry assessed using isokinetic dynamometry[32], suggesting a potential surrogate or complementary neuromuscular measure for a known risk factor for ACL reinjury (i.e. quadriceps strength deficits)[18]. Vertical jump force-time asymmetries also persist in athletes who have returned to sport after ACLR[20–22] and following lower body injury[33]. While there is currently no scientific evidence linking return to sport outcomes after ACLR with elevated vertical jump force-time asymmetries, jump asymmetry testing appears to be sensitive to the recovery process after ACLR. Figure 11 depicts the recovery in CMJ concentric phase asymmetry and SJ late takeoff phase asymmetry for 20 ACLR competitive alpine skiers who performed serial testing throughout the return to health, return to sport and return to performance transitions.

It took just over one year for the mean interlimb asymmetry index (dashed blue line) to fall below 10%, a common threshold used for return to sport readiness. However, more than 2 years were required for the interlimb asymmetry index to return to a value comparable to that of non-injured alpine skiers. This notion is consistent with other reports that suggest more than 2 years may be required for recovery after ACLR[25,41]. Building sport-specific recovery timelines using vertical jump asymmetry testing can be valuable for sport science and sport medicine practitioners in order to manage coach/athlete expectations after injury, improve injury recovery forecasting and to develop recovery norms against which new rehabilitation strategies or medical interventions can be compared.

However, a reductionist interpretation of vertical jump asymmetry testing can be misleading. For example, a well-known effect of lower limb injury is contralateral limb strength loss. An athlete with ACLR who has two symmetrical, but weak lower limbs may have different challenges with a safe return to sport compared to an athlete who has two strong lower limbs that are asymmetrical (e.g. an asymmetry index > 20%). Further, CMJ and SJ testing may not reflect the sport-specific demands. For instance, alpine ski racing is energetically demanding, and skiers are exposed to high force eccentric/quasi-isometric loading that exceed the forces produced in the vertical jump. Other sports like basketball or soccer may have a greater emphasis on single leg propulsion/energy absorption. Interlimb asymmetries are also task-dependent[40] and movement phase dependent (c.f. Figure 7).

Consequently, practitioners may be best served by building a sport-specific envelope of function and a risk profile for athletes returning to sport after ACLR[42]. While vertical jump asymmetry testing using a dual force plate system is practical and conducive for routine athlete monitoring, additional assessments may be useful when evaluating ACLR athletes. Tests of interest include single leg jumping and landing tests[19], repeated jump testing to assess the effects of performance fatigability on force-time characteristics[21,43], and loaded vertical jump testing (functional force-velocity profiles). Consider the example shown in Figure 12 depicting a SJ force-time curve for the first jump and the last jump of an 80-second repeated SJ test in which the athlete performed one jump every 4 seconds (total jumps: n=20). The 80-second repeated SJ test was developed for alpine ski racers to assess neuromuscular function over a time frame comparable to a typical race[21]. Outcome measures of interest include a fatigue index (drop-off in mechanical muscle power from the start to the end of the test), total mechanical power over the test and the acute effects of fatigue on interlimb asymmetries.

The force-time curves in figure 12 also show the athlete becoming more symmetrical with fatigue consequent to a reduction in force generated by the non-injured limb. The force-time curve shape in the final jump is also bimodal, suggesting a potential change in the vertical jump strategy. As the contralateral limb is particularly susceptible to ACL injury after a primary ACL injury is sustained[26,41], objective assessments that challenge the athlete in a sport-specific manner in terms of the energetic demands can be helpful for exposing trainable deficits for the non-injured and injured limbs alike.

Summary recommendations for incorporating dual force plate asymmetry testing with ACL injured athletes include:

- There is limited scientific evidence supporting return to sport testing batteries after ACLR and no statistical relationship between elevated vertical jump interlimb asymmetries and outcome after ACLR, so caution is warranted.
- Vertical jump asymmetries persist in athletes with ACLR and lower body injuries despite their return to sport. However, force-time interlimb asymmetries diminish over time, suggesting the relevance of vertical jump asymmetry testing as a monitoring tool for sport science/sport medicine practitioners.
- Athletes with ACLR may present initially with very high vertical jump interlimb asymmetries (> 50%). It often takes more than 1 year for the asymmetry index to return below 10%, and more than 2 years may be required for interlimb asymmetries to return to values observed in non-injured athletes.
- An interlimb asymmetry index is inherently problematic. What if an athlete is symmetrical but has two weak lower limbs? What if an athlete has two strong limbs but is asymmetrical? These questions are important to consider.
- Sport science and sport medicine practitioners may be best served by developing a return to sport testing battery that is sport-specific and uses multiple tests to build a risk profile aimed at exposing trainable deficits.

FUTURE DIRECTIONS

More scientific inquiry is required to examine the value of vertical jump interlimb asymmetry testing for assessing athletes with ACLR throughout the return to health, return to sport and return to performance transition. Dual force plate systems are becoming increasingly common in clinical and high-performance sport settings. Practitioners should be careful to ensure data quality given the implications of return to sport decision making. There are no short cuts for ensuring a force plate is working properly. Routine calibration is essential to limit the possibility a malfunctioning force plate is misconstrued for a performance or functional change in an athlete with ACLR.

Vertical jump asymmetries are variable and task dependent. Consequently, more sophisticated approaches to force-time curve analysis like statistical parametric mapping and machine learning may provide sport science and sport medicine practitioners with better insights and predictive validity. Further, many commercially available systems ignore the bulk of the ground reaction force signal including horizontal forces. There may be valuable information in these planes, especially when evaluating athletes with ACLR. The high fidelity nature of the data obtained from dual force plate asymmetry testing and the many unanswered questions will provide sport science and sport medicine practitioners with plenty of fruitful research opportunities to explore new approaches for optimizing the return to health, return to sport and return to performance transition for athletes recovering from ACLR.

References

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