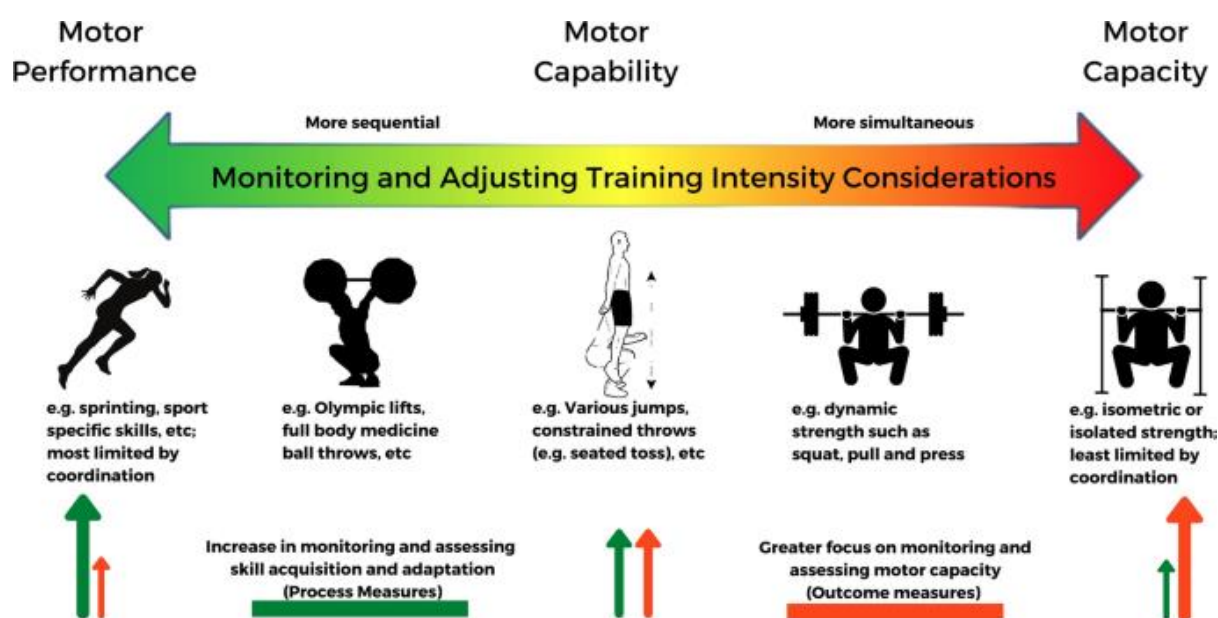


Module 2. Lower Limb Isometric Tests

Dr. Rhys-Morris and Dr. Daniel Cohen

Muscular strength, defined as the ability to exert force on an external object or resistance (Suchomel et al., 2018), is a critical motor capacity or capability that contributes to a number of aspects of motor performance, such as vertical jump, sprinting, and change of direction (Brady et al., 2020). Periodic assessment or “profiling” (such as in preseason or at the beginning of the training cycle) of motor performance, motor capabilities, and motor capacity (figure 1: Continuum of performance) is common practice within performance settings to identify athletes' strengths and weaknesses and inform individualized training prescription.

Figure 1: Continuum of performance



From: Suchomel et al, 2021, p 2059

Table 1. Athlete’s profiling

Construct	Performance	Capability	Capacity
Description	Does do during competition	Can do during competition	Can do in a controlled environment

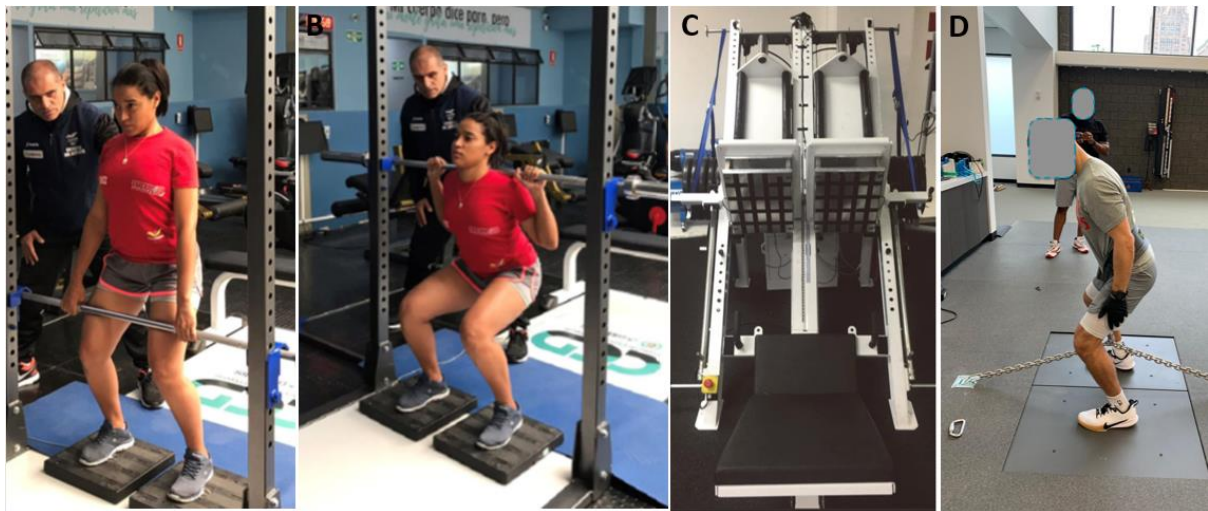
Source: Prepared by the author

“Isometric Strength Testing”

Within the continuum of performance, it is clear that muscular strength is a very important motor capacity underpinning a number of performance and capabilities. While a variety of testing regimens exist to test concentric and eccentric strength dynamic strength, isometric strength is commonly used to assess maximal force production (Jaric, 2002). There are multiple methods of isometric multi-joint or single joint strength assessment in practice and in the literature. While single joint assessments – typically knee extension - are common in laboratory-based research which prioritize highly standardized and control conditions and joint angles (an important determinant of force production). However, Tillin et al.,(2013) recommends multi-joint assessments in athletic populations, based on the specific neural and mechanical conditions associated with motor capability and performance (e.g., the relationship shared between sprinting, jumping and strength). The two isometric multi-joint assessments most commonly implemented to examine lower limb extensor strength are the isometric mid-thigh pull (IMTP) and isometric-squat (ISq), and are therefore the focus of discussion in this section. In practice however, the belt-squat (Layer et al., 2018), a variant of the ISq, (described in Course “Injury and Rehabilitation Kinetics and Kinematics”, Module 4) and the force platform isometric leg press (Harden et al., 2018; Martinopoulou et al., 2022), are also useful alternatives to evaluate lower limb extension even though they are far less well described in the literature than the IMTP and IS. However, it is worth noting that for those with lower back issues, significantly lower spinal loading and higher knee and ankle moment and peak force is observed in the belt squat versus the ISq (Layer et al., 2018), with the leg press also expected to reduce this load. It has also been highlighted that grip strength may be a limiting factor in IMTP performance (Rhodes et al., 2022). As such, despite the large volume of literature for IMTP and ISq, practitioners should be aware of, and may want to consider these alternatives.

The IMTP and IS are both closed-chain, multi-joint isometric assessments. These tests are performed at specific joint angles are highly reliable measures of peak force (maximum strength) (Lum, Haff and Barbosa, 2020; Blazevich et al., 2002) and performed on force platforms that can be used to assess both maximum force-generating capacity and force-time derivatives – such as rate of production across different epochs.

Figure 2: Isometric Lower Limb Extension Tests



Sources: prepared by the author, adapted from A,B: Rodríguez Zárata et al., 2018, C: Harden et al., 2018, D: Antflick J.

A: Isometric Mid-Thigh Pull (IMTP) B: Isometric Squat (ISq) C: Isometric Leg Press D: Isometric Belt-Squat

A, B and D typically performed bilaterally but can be performed unilaterally. C typically performed unilaterally but can also be performed bilaterally.

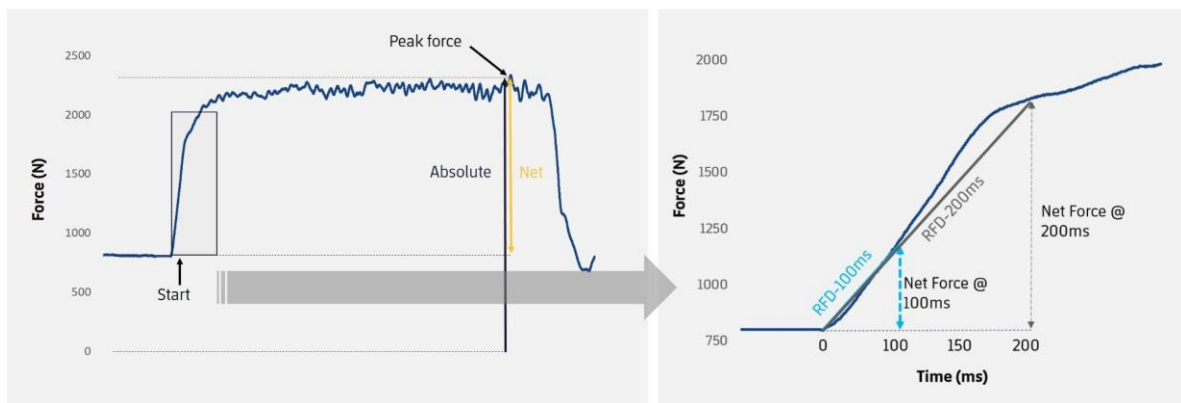
“The Method – Isometric Mid-Thigh Pull”

Importantly, for practitioners using the test for monitoring change, IMTP peak force is highly reliable and is simple and relatively quick to perform. The IMTP is also a safe alternative compared to the substantially more time-consuming 1 repetition maximum (1 RM) tests, which also raise some concerns in terms of fatigue and risk of injury during assessment (Beckham et al., 2013; Brady et al., 2020). It is proposed that when working with youth populations without a long training history, the use of the IMTP offers a valuable insight into their maximal extension strength capacity without the skill acquisition required to express maximum strength in a 1 RM squat or Olympic lift for example. Nonetheless, ensuring that a standardized and repeatable protocol to perform the IMTP is in place is critical to obtaining accurate data.

The IMTP literature has accumulated over 25 years, with a range of methodological approaches to consider when implementing the test. Dos’Santos et al., (2019) provides a relatively recent comprehensive review of protocols and interpretation of the IMTP with an approach that follows that the IMTP should be performed with the athlete positioned as they would be in the second pull phase of the clean, where they produce the most force (Garhammer, 1993; Haff et al., 1997). Specifically, an optimal knee angle of 125-145° and a hip angle of 140-150°. Practitioners can change the height of the bar to achieve these angles and adjust them to ensure the athlete is in a position where they feel comfortable. As for all tests used for monitoring change in an athlete, it is more important to ensure precise standardization within than between – so note these final positions, including stance, so other

practitioners can repeat this set up in the test. Other postural aspects of the protocol to coach are an upright torso, slight flexion in the knee resulting in some dorsiflexion, shoulder girdle retracted and depressed, shoulders above or slightly behind the vertical plane of the bar, feet roughly centred under the bar approximately hip-width apart, knees underneath and in front of the bar, and thighs in contact with the bar (close to the inguinal crease dependent on limb lengths). Prior to the maximal effort “pull”, the athlete should also remove ‘any slack’ (e.g. elbow flexion, shoulder girdle elevation/protraction) in the system to avoid any changes in joint angles during the maximal effort, this is also referred to as “pre-tension”.

Figure 3 a.b: “Ideal” Isometric Mid-Thigh Pull Force-Time curve



Source: prepared by the author

A (left panel): “Ideal” IMTP force-time showing peak force (absolute=total value, net=total - bodyweight). B (right panel): the first 200 ms of the pull magnified to show force@ and RFD metrics at 100 and 200 ms. Net force@ metrics are expressed in newtons - force applied between start of pull and x time point, RFD (rate of force development) metrics are expressed in N/s and = force change/time epoch (e.g. 100 or 200 ms). RFD may also be expressed relative to body weight as N/s/kg. Note that the overall appearance of the ISq curve is similar.

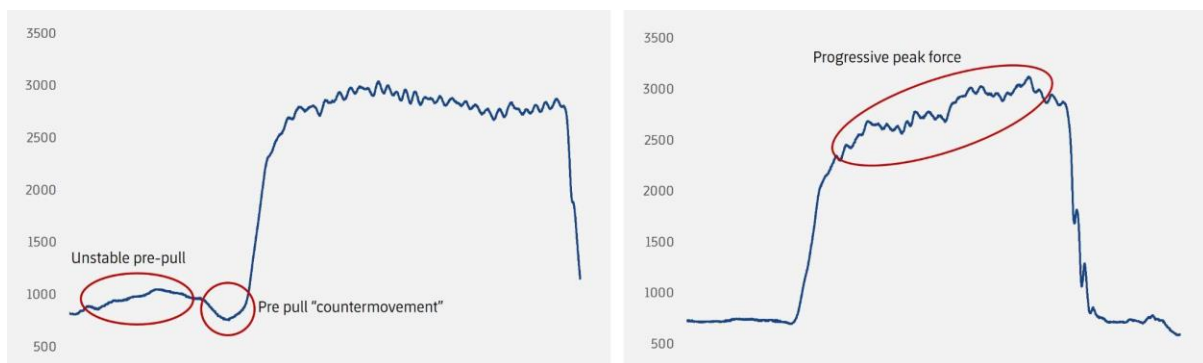
The reliability of any performance test is essential to ascertain and is a marker of test consistency. Reliability can be determined and expressed in a number of ways, depending both on Standard Error of Measurement (SEM) and on the ability range (standard deviation, SD) of athletes taking an assessment (Tighe et al., 2010). By quantifying the reliability of force-time metrics using these indicators in our athlete group and individual athletes, we can define which variables among those recommended or cited in the literature are most appropriate to report systematically and which might need to be considered with caution. A common practice within sport science is to also report intraclass correlation coefficient (ICC), coefficient of variation (CV) with 90% confidence intervals (90% CI) calculated (Atkinson & Nevill, 1998; Haff et al., 2015; Hopkins, 2000). The ICC gives information about the degree of consistency and agreement between two sets of data. However, an ICC will not detect any systematic errors, and therefore, it is possible to have two sets of highly correlated scores that are not repeatable. The CV estimates measurement error and is the typical CV expression (Hopkins, 2015).

Evidence suggests that of the IMTP performance variables, peak force is highly reliable (ICC = 0.89 - 0.99, CV = 1.7–5%) and can determine the smallest detectable change (~8.5%, Brady et al., 2020) and practitioners should consider this as a standard in reports, whether absolute or relative. A number of early studies also reported that force-time characteristics, such as peak rate of force development (pRFD) as reliable (ICC > 0.8) (Haff et al., 2005; Kawamori et al., 2006; Stone et al., 2003; West et al., 2011). Additionally, Kraska et al. (2009) reported force at 90 ms and force at 250 ms to be reliable (ICC \geq 0.94). However, reporting ICC's without CV's and, in most cases, CI's makes it hard to assess whether these findings are reliable. Beckham et al., (2012) first reported both IMTP ICC's and CV's and also established the reliability of PF (ICC = 0.92 and CV = 5%) and \leq 4.3% across several studies (Beckham et al., 2014; Haff et al., 2015; Thomas et al., 2015). Similar PF reliability is reported among junior athletes, including competitive surfers (ICC = 0.98 and CV = 4.2%) (Secomb et al., 2015) and youth soccer players (ICC=0.98; CV = 4.91%) (Morris et al., 2018). collectively, ICC's and CV's of RFD measures of > 10% (an arbitrary threshold for "good" reliability. CVs > 10% are reported despite ICC values > 0.8 (Beckham et al., 2014; Thomas et al., 2015). Haff et al. (2015) reported a number of RFD across various epochs which met both the criteria of an ICC > 0.8 and CV < 10% while average RFD was outside the acceptable levels of reliability (ICC = 0.74 and CV > 10%) (Haff et al., 2015). Overall they observed better reliability in epochs (e.g.,RFD 0–50 ms, 0–250 ms) than peak RFD and average RFD measures with an ICC of 0.90 (Haff et al., 2015).

Research on the reliability of the ISq is limited compared to that available on the IMTP. Research has examined reliability of variables at various knee joint angles, also finding peak force to be the most reliable variable with ICC's of \geq 0.97 (Bazylar et al., 2015; Blazeovich et al., 2002; Hart et al., 2012) and $r \geq$ 0.98 (Cormie et al., 2007; Nuzzo et al., 2008). Hart et al., (2012) assessed CV and ICC in both bilateral and unilateral ISq and reported ICC = 0.97 and CV = 3.6% of peak force in bilateral ISq at a knee angle of 140° (and unilaterally at the same knee angle (ICC = 0.98 and CV = 3.6%). There is however limited research on the reliability of other variables such as RFD epochs, peak RFD or impulse epochs in the ISq.

IMTP and ISq variable reliability (particularly of RFD) is affected by familiarization sessions. Drake et al., (2018) suggested that a minimum of three familiarization sessions is required to stabilize the learning effect when using these tests. This is important for practitioners to understand when they start implementing these tests.

Figure 4.a.b: Isometric Mid-Thigh Pull: Sample issues & errors



Source: prepared by the author

A (left panel): Errors in execution often observed during the IMTP (which can also be observed in the ISq) that can affect start detection and calculations of RFD epochs. B (right panel): Progressive attainment of peak force after achieving a large proportion of it rapidly is a phenomena that might not be considered an error but suggests that the athlete is not completely adhering to the instruction to produce maximum force as rapidly as possible.

Protocol

The most efficient way to set up an athlete is to ask them to self-select the second-pull position of the clean. Once they are in the position, adjust the bar height to ensure you achieve the optimal knee (125-145°) and a hip angle (140-150°). Once you have your desired joint angles, take note of the bar height, foot position and grip width. This will ensure the test procedures are repeatable for next time. Early work, has demonstrated different positions across the hip and knee will impact the IMTP performance. While authors suggest applying minimal pre-tension, this is important to avoid any joint angle changes when maximally testing. While this body of work has not really been considered, the need to minimize pre-tension but ensure the athlete has taken the 'slack' out of the system are equally important. Authors suggest that the live force trace is visible (on laptop or TV screen), to ensure there is no deviation from the bodyweight force trace.

The Method – Isometric Squat

Similar to the IMTP, the ISq has various joint angles reported within the literature (90-150°) (Blazevich et al., 2002; Wilson et al., 1995). Unlike the IMTP, which is said to replicate the second-pull position of the clean, the ISq is more commonly varied according to the joint position most relevant to the action of interest or as Bazylar et al., (2015) suggests, the joint angle(s) that corresponds to that which in the dynamic movement of interest force output is the highest (120° knee angle). Another angle to consider is the position in the lift when mechanical advantage is at the lowest, specifically, the "sticking region" in the squat task (90° knee angle for the back squat). Thus, the author suggests an assessment of angles 90-120° within the ISq to evaluate the athlete's strength capability enough to provide meaningful data for the practitioners to use. A knee angle of 90°–100° is most commonly used in research

(Bazyler et al., 2015; Blazeovich et al., 2002; Cormie et al., 2007; Loturco et al., 2016; Newton et al., 2002; Young & Bilby, 1993) and therefore facilitates comparisons with published data, although some studies used a knee angle of 140° (Dumke, Pfaffenroth, McBride, & McCauley, 2010; Nuzzo et al., 2008).

Force-Time curve analysis

These testing procedures usually occur within a customizable rack that will allow the athletes to push/pull the immovable bar for at least 5 seconds. An example of a customizable rack can be seen in figure 4. The analysis and reliability of the force-time curve requires consistency from practitioners for both the procedure and the calculation of variables from the tests. Once the practitioners and athletes are familiar with the testing procedures, identifying movements is essential to calculate the variables. Historically, researchers have used 40 N arbitrary thresholds above the mean body weight (West, 2011). Still, recent work defined the start point as when the first derivative exceeded the mean plus 5 SDs for time-specific force values for the most accurate and reliable results. This threshold eliminates the potential influence of noise (Dos'Santos et al., 2017). Table 2 demonstrates common variables calculated from force-time curves. Practitioners need to state how they have calculated their variables to allow for replication should they need to (or others).

Figure 5: Customizable isometric rack



Source: Human Measurements Technologies; Vald Performance
Athlete shown performing IMTP, with rack adjustable allowing ISq and other isometric tests to be performed

Table 2. Calculations of variables

Variable	Abbreviation	Value	Calculation
Absolute peak force	PF	N	PF produced minus the participant's body weight
Relative peak force	RPF	N/kg	Absolute PF ÷ participants body mass (kg)
Allometric scaled peak force	AlloPF	$N/kg^{0.67}$	Absolute PF ÷ participants body mass (kg) ^{0.67}
Rate of force development	RFD	N/s	$\Delta\text{Force}/\Delta\text{Time}$
Peak rate of force development	pRFD	N/s	Highest RFD during sampling windows
Average rate of force development	avgRFD	N/s	PF achieved and time between initiation of pull (0) and PF values
Impulse	IP	N.s	$\text{avgForce} \times \Delta\text{Time}$
Index of explosiveness	IES	N/s	Same as avgRFD
Reactivity coefficient	RC		$PF/(TPF \times BW)$
S-gradient	SG		$PF_{0.5}/TPF_{0.5}$
A-gradient	AG		$PF_{0.5}/(TPF - TPF_{0.5})$
Starting strength	F30 ms	N/s	$(\Delta\text{Force}/30 \text{ ms})$

Source: prepared by the author.

Normative Values

How strong is strong enough? Sport Scientists are always posing this question, and it is clear to say you can never be too strong. Normative data helps create an athlete's profile and allows the coach to determine the direction and content of their training programmes (Loturco et al., 2016) and evaluate the effects of training on performance (Mangine et al., 2015). Thus, understanding athletic norms can be beneficial for those working in the industry. Still, practitioners must be aware of their population (training age, level of play, gender, etc.) when making comparisons, as this will influence the interpretation of the findings. For example, the published normative data is usually based on group averages and the range of scores around the mean (SDs, 95% CI, Media, etc.). Comparing test results will inform the coach how their athlete rated compared to the population average, not necessarily the best of that population.

Additionally, the results should be normalized for body mass, as the inclusion of body mass will inflate results. Normative data provides a reference point for the interpretation of the results, but should be used with caution. When using the literature to compare against, it is crucial that the practitioner can access details of protocols and how data was collected, considering such factors as familiarisation, sampling frequency of force platforms, start detection threshold and instructions given. Below are examples of sporting populations and normative values for maximum strength (peak force) and normalized maximum strength

(relative peak force). Interestingly, some normative values for similar sports have a wide range of data . For example, rugby players have reported a range from 1855 to 2100 for youth players and anywhere from 2500 to 2900 N for senior players. Anecdotally, these values appear low, especially from an absolute perspective. For example, unpublished data in elite boxer’s, have produced peak force values of 3000 N and relative peak force of around 41 Newtons per kilogram of body mass. In addition, Beckham et al., (2012 and 2013) published values for weightlifters. The author's non-elite group produced greater PF (5942 ± 844) vs elite published peak force values (5829 ± 867). While in other sports, playing status may not matter as much with the IMTP because the sport is based on different performance variables, but weightlifting is primarily based on force production, and therefore, caution should be taken when interpreting perceived normative values.

Table 3. IMTP and ISqT peak force normative values.

Test	Study	n	Participants	Sex	Body mass (kg)	Peak force		RFD (N/s)	RFD type
						Absolute (N)	Relative (N/kg)		
IMTP	Haff et al. (1997)	8	Trained weightlifters	M	95.1 ± 4.4	2,847 ± 256		29,693 ± 3,070	Peak
IMTP	Stone et al. (2003)	11	Collegiate Throwers	M & F	101.3 ± 25.3	3,002 ± 933**	29.1 ± 9.1**	15,000–18,000**	Peak
IMTP	Stone et al. (2004)	20	National Track Cyclists	M & F	77.6 ± 13.6	3,591 ± 875**	46.1 ± 7.0**	12,576 ± 4,230**	Peak
IMTP	Stone et al. (2005)	16	Elite Weightlifters	M	83.4 ± 27.0	5,127 ± 1,056**	54.0 ± 51**		
				F	68.9 ± 18.5	3,510 ± 587**	48.8 ± 9.5**		
IMTP	Haff et al. (2005)	6	Elite Weightlifters	F	82.8 ± 18.9	3,649 ± 824	43.4 ± 5.1	13,997 ± 4,450	Peak
IMTP	Kawamori et al. (2006)	8	Collegiate Weightlifters	M	85.1 ± 3.3	3,178 ± 285	37.4 ± 3.4	22,008 ± 4,270	Peak
IMTP	McGuigan et al. (2006)	8	NCAA D3 Wrestling	M	78.0 ± 4.2	2,645 ± 465**	33.9 ± 5.9**	32,063 ± 18,834**	Peak
IMTP	Nuzzo et al. (2008)	12	NCAA D1 (AF & Athletics)	M	90.1 ± 14.8	3,144 ± 792*	35.2 ± 6.8*	3,556 ± 1,026*	Peak
IMTP	McGuigan and Winchester (2008)	22	D1 American Footballers	M	107.6 ± 22.9	2,159 ± 218*		13,489 ± 4,041*	Unknown
IMTP	Kraska et al. (2009)	63	Collegiate athletes	M & F	72.9 ± 19.6	2,138 ± 323*		12,175 ± 4,338*	Peak

IMTP	West et al. (2011)	39	Professional rugby league	M	97.0 ± 8.2	2,529 ± 398		23,653 ± 7,424	Peak
IMTP	Leary et al. (2012)	12	Recreational golfers	M	77.0 ± 9.8	2,138 ± 323*			
IMTP	Beckham et al. (2012)	14	Powerlifters	M	109.9 ± 20.0	5,829 ± 867*	±53.0 ± 7.9*		
IMTP	Beckham et al. (2013)	12	Sub-elite weightlifters	M	96.0 ± 19.2	5,942 ± 844*	±63.9 ± 14.3*		
				F	66.6 ± 4.8	3,743 ± 42.4*	±56.4 ± 4.7*		
IMTP	Beckham et al. (2014)	106	NCAA athletes	D1 M & F	76.1 ± 12.7	3,802 ± 1,053*	±50.0 ± 13.8*	±6,544 ± 3,427	±0–200 ms
IMTP	Haff et al. (2015)	12	Volleyball players	F	68.6 ± 8.2	2,507 ± 421*			
IMTP	Thomas et al. (2015)	22	College athletes	M	78.1 ± 10.8	2,709 ± 587*	±34.6 ± 5.3*	±10,899 ± 4,543	±Peak
IMTP	Thomas, Comfort et al., (2015)	14	Collegiate Soccer & RL	M	72.8 ± 9.4	2,752 ± 546*			
IMTP	Secomb et al. (2015)	30	Competitive junior surfers	M & F	54.8 ± 12.1	1,520 ± 412*			
IMTP	Darrall-Jones et al. (2015)	67	Academy rugby players	M—U16	79.4 ± 12.8	2,158 ± 310*	±28.1 ± 0.3*		
				M—U18	88.3 ± 11.9	2,561 ± 339*	±29.9 ± 2.9*		
				M—U21	98.3 ± 10.4	3,105 ± 354*	±31.4 ± 2.8*		
IMTP	McMahon et al. (2015)	15	Collegiate field sport athletes	M		3,045 ± 497*			
IMTP	Wang et al. (2016)	15	Collegiate Rugby Union	M	86.5 ± 14.2	2,945 ± 618			
IMTP	Parsonage et al. (2016)		Competitive surfers	M	72.1 ± 8.8	2,422 ± 489**	±33.6 ± 5.1**		
				F	59.1 ± 5.4	1,644 ± 252**	±27.8 ± 3.3**		
IMTP	Beattie et al. (2016)	6	Competitive road cyclist	M	69.1 ± 3.6		±34.9 ± 6.0*		
IMTP	Dobbin et al. (2017)	56	Rugby league players	M		2,533 ± 243*—			Senior players

dynamic performances such as jump height (Kraska et al., 2009; Kawamori et al., 2006; Lum & Joseph, 2020; Comfort et al., 2014), sprint time and velocity (Lum & Joseph, 2019; Comfort et al., 2014, Brady, et al., 2019; Seitz et al., 2014; Townsend et al., 2019), and change of direction test time (Thomas et al., 2015; Thomas et al., 2017; Thomas et al., 2016; Spiteri et al., 2014). Mason et al (2021) reported associations between IMTP metrics and horizontal movement characteristics including acceleration, maximal sprint speed and 505 change of direction test in a small sample (n=11) of professional development soccer players (age: 20±2 years). Max sprint speed significantly correlated with IMTP absolute peak force, relative force@150, and @200 ms and peak force and (r=0.57, r=0.51, r=0.66, and r=0.76 respectively); COD time correlated with relative force@150 and @ 200 ms and (r=-0.68 and r=-0.60 respectively) and 10 m acceleration with relative force@200 and peak force (r=-0.55 and r=-0.53).

Due to these relationships, it is essential to assess an athlete's lower body strength to monitor the athlete's training progression and examine the effectiveness of the training program. The force-time data collected during these tests are strongly correlated to various markers of dynamic sports performances such as jumping (Kraska et al., 2009; Kawamori et al., 2006; Lum & Joseph, 2019; Comfort et al., 2014), sprinting (Lun & Joseph, 2019; Comfort et al., 2014; Townsend et al., 2019; Kuki et al., 2017), throwing (Stone et al., 2003) boxing (Loturco et al., 2016), golf swing (leary et al., 2012), cycling (Stone et al., 2004) and kayaking (Van Someran & Howatson, 2008). While there have been reports of strong associations, some studies have demonstrated no relationships between IMTP and jump height (Nuzzo et al., 2008). Brady et al., (2019) also showed no association between force-time characteristics obtained from IMTP and ISq with sprint acceleration performance in female sprint athletes. Northeast et al., (2017) demonstrated no statistically significant relationship between IMTP force at 100 Ms and sprint time in professional soccer players, while Dos'Santos et al. (2018) showed no association between squat jump height force-time characteristics. Of interest, Dos'Santos et al. (2018) suggests using a heterogeneous cohort of athletes and not a homogenous sample. Finally, an agreement of instruction needs to be clear and consistent with previous methods. Dos'Santos et al. (2018) does suggest the use of instruction may have impacted the SJ performance and subsequent relationship with the IMTP.

Finally, those studies that have shown no relationship with the dynamic tasks, such as sprinting and force-time characteristics (Northeast et al., 2017; Brady et al., 2019), may be a consequence of the relative force contribution that influences whole-body displacement when compared to absolute force output. As linear sprint performance depends on body mass acceleration, rather than overcoming inertia and air resistance, the ability to produce high levels of force relative to body mass have been proposed as superior to absolute peak force measures. Thus, the expression of force at 100 ms may not be appropriate for sprinting, whilst the authors reported relative peak force related to sprinting performance (Northeast et al., 2017). Equally, the athletes used in the Northeast et al., (2017) study were deemed to be weak, and thus, caution should be used when interpreting these findings.

It has been shown that isometric test force-time characteristics are moderate to very strongly correlated to dynamic performances of the upper and lower limbs and the performance of sports-specific movements, indicating that isometric force-time characteristics were able to provide insights into the force production capability of an athlete for performing the movements. However, practitioners should still measure and use specific testing protocols, given some limitations with the isometric testing. The biggest drawback is the inability to program strength or power training sessions based on the Iso test data. For example, peak force, from either the IMTP or ISq, related well to squat performance, but this cannot be used to plan training loads with squat performance. Blazeovich et al. (2002) reported an 8.5% difference to actual 1RM load when the peak force produced during ISq was used to predict 1RM load. To date, no further improvement in standard error has been reported or use of a prediction equation to convert peak force from either test into a training load.

While the prescription of training load is missing, the force-time data isometric testing offers is fruitful. Capturing this data and information can help monitor, adapt and modify training plans with athletes. For example, the ground reaction forces captured using force plates will detect changes in force and subsequent metrics. While no specific testable hypothesis has questioned this (force plates are viewed as the gold standard for detecting changes in GRF), practitioners still need to be aware of the system's noise (electrical signal noise). Typical noise can be captured by averaging sample GRF data (say 1 second). This will approximate the system noise, which practitioners can use to detect meaningful changes in force above and beyond what the plate is capturing. Depending on the force plate system, environment (such as flooring, the housing of the plates, the rigs, etc.) typical noise, captured from 1000 Hz will usually be around 9-10 Newtons (around 0.9 kg). In addition, once the practitioners have identified the variation in performance from the athlete and certain metrics (coefficient variation), they can use both bits of information to ascertain a meaningful change in the practitioner without being too process heavy. The application and use of isometric testing across various populations is valuable, providing practitioners with meaningful data. While there are limitations to the tests, the benefits outweigh these.

Individual Case Study – Elite Boxer

Boxing is a sport that requires the physical capacities from all the common components of fitness (strength, speed power, aerobic and anaerobic, etc.), but it is not uncommon for boxers. According to the unified rules of professional boxing, three judges award points according to the “power and quantity” of punches landed (Commission, 2005). Accordingly, strength and power are key determinants of success (Chaabène et al., 2015; Halperin et al., 2016; Hembrough et al., 2016). Boxing matches are contested in predefined weight categories (Commission, 2005), with boxers commonly aiming to compete in a category below their

natural weight to avoid conceding size, strength and power to an opponent (Halperin et al., 2016; Morton et al., 2010; Pettersson et al., 2013). This highlights the importance of monitoring strength (and other metrics). However, traditional use of RM testing is not appropriate with athletes who are making weight, and are at a potential risk of injury. The IMTP, however, was used due to the previous benefits described above, but not without some limitations. So the case study followed the athlete until the final week of his bout. The results that we captured include maximum values (absolute and relative) and force at certain time-epochs.

Table 4. Longitudinal IMTP force time data in an elite boxer

Week	Force at 150 ms	Force at 250 ms	Peak Force	Relative Peak Force	Body weight
1	1130	1485	2770	34	81.4
2	1063	1658	2936	36.5	80.3
3	1185	1703	3039	38.4	79.1
4	1294	1917	3102	39.4	78.8
5	1297	1927	3003	38.7	77.5
6	1499	2071	2948	38.7	76.2
7	1306	1940	2972	39.2	75.9
Fight Week					

Source: Prepared by the author

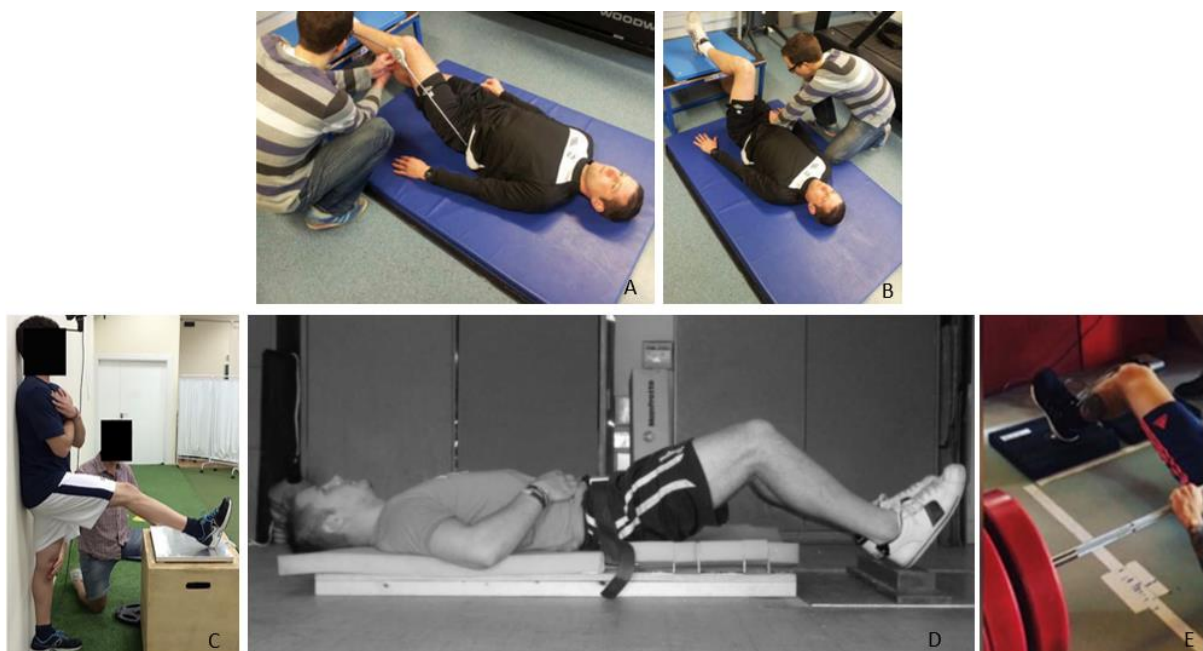
The above data above is a typical training camp the boxer has gone through, which has included weight-loss along with a periodized strength and power intervention. Even more interesting is the use of the IMTP to capture the athlete's maximum and force expression over that period. As you can see, there is a slight decline in absolute force expression, but the athlete's relative force expression has increased from week 1 to week 7. This is imperative given the association with expression of force per kg of body mass. In addition, it is not uncommon for the boxer's to regain weight after the weigh in, with some evidence suggesting mixed martial artist regain around ~ 10% body mass (Kirk et al., 2020). This is very important as the absolute performance with an increased mass will improve, but perhaps the relative force expression will decrease. The IMTP allows the tracking and monitoring of these changes.

Posterior Chain Tests

Isometric Posterior Chain (IPC) or hamstring tests, are after the IMTP, one of the most widely implemented lower extremity isometric assessments in high-performance settings. IPC and other hamstring/posterior chain tests are most commonly used in sports with a sprint or repeated high-speed running component in which the hamstring strain is the most common injury. Although the hamstring muscle group is critical to sprint performance (Pandy et al., 2021), the majority of the literature related to measurement of hamstring neuromuscular characteristics is related to identifying risk factors for primary or recurrence of hamstring strain injuries (HSIs). HSI's are one of the most common injuries in professional soccer and other repeated sprint sports, accounting for approximately 12% of all muscular injuries in football (Ekstrand et al., 2011). While time-loss burden per injury may not be high unless there is tendon involvement (Taberner et al., 2022), the high incidence and recurrence rate (Ekstrand et al., 2011) warrant the attention given to the injury.

IPC tests can be performed with various devices and for practitioners without access to force platform technology, alternative means to capture IPC-hamstring peak force (Wollin et al., 2016; Lahti et al., 2020) are shown in figure 12, at the end of this section. There are also a number of variants of force platform IPC tests, described in the literature (McCall et al., 2015; Matinlauri et al., 2019; Goodwin & Bull, 2021) and or evolved and implemented in practice (figure 6, panel E).

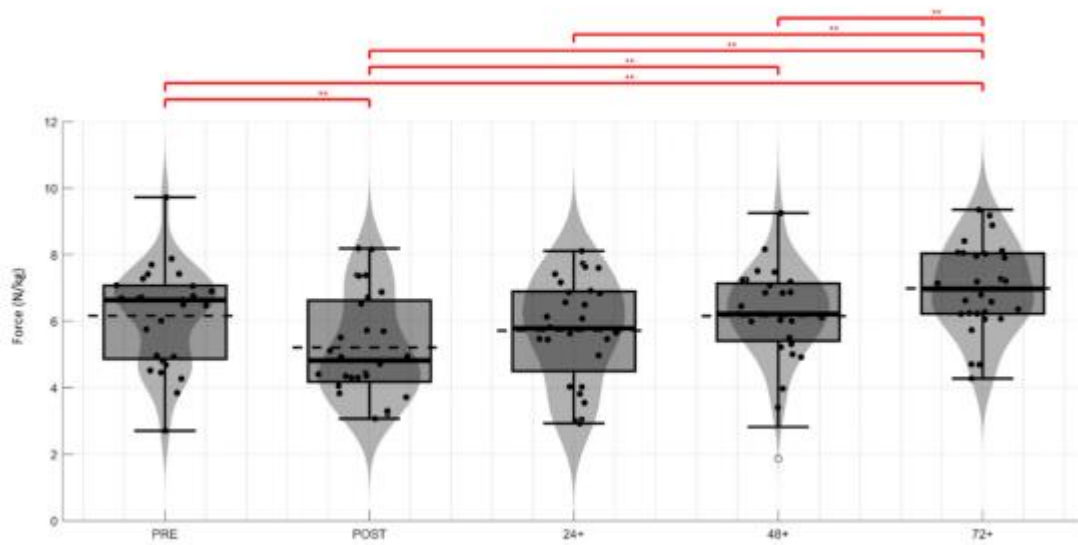
Figure 6: Supine closed-chain force platform isometric posterior chain tests



Sources: A, B: McCall et al., 2015; C: Matinlauri et al., 2019; D: Goodwin & Bull, 2021 E. author's own
A: 30° and B:90° bridge C: Standing 90°:20° hands on chest D: floor-bilateral hip bridge with safety belt restraint
E: floor-unilateral hip bridge, the loaded bar used to prevent hip extension

As discussed in Course “Injury and Rehabilitation Kinetics and Kinematics” with reference to strength measurements during rehabilitation, the “gold standard” and well established means of assessing hamstring muscle strength is via isokinetic dynamometry. As highlighted, there are barriers to the routine and frequent use of this technology, its limited availability (due to cost) and if it is available the relatively time-consuming nature of the assessment, make it impractical in high-performance and particularly team sport environments. The Nordic hamstring assessment (“Nordbord”) is an alternative means to rapidly evaluate dynamic (eccentric) hamstrings/posterior chain muscle strength and asymmetry, with evidence demonstrating cutpoints for elevated injury risk (Timmins et al., 2016; Bourne et al., 2015). While isometric hamstring assessment using a handheld dynamometer or manual testing has been used for decades by physiotherapists in RTS following hamstring injury, it is only relatively recently that the IPC tests have been reported in the regular monitoring of healthy athletes and integrated more extensively throughout the hamstring rehabilitation pathway (Taberner & Cohen, 2018; Taberner et al., 2020; Taberner et al., 2022) - including frequent assessments and the use of peak force and RFD data to inform progression during rehabilitation. To the author’s knowledge Schache et al (2011) first described the use of IPC tests, as an in-season monitoring tool in professional sports. They outlined two isometric supine unilateral posterior lower limb maximal effort, 3 second tests performed at either 90°:90° (knee:hip flexion) (90°:90°) or 30° (knee flexion). In this case report, a HSI is preceded by a player manifesting an anomalous trend in asymmetry (relative to the team) in IPC performance, which was being routinely monitored on a weekly basis using a pressure cuff. Nedelec et al (2014) subsequently demonstrated significant decreases in peak values in both positions following competitive soccer, confirming the sensitivity of this isometric test to residual fatigue induced by match play. McCall et al (2015) first demonstrated the same tests being assessed using force platforms and reported acute post-match decrements in peak force in both positions in professional players and the interday reliability of the test. In academy footballers, Constantine et al. (2019), examined the IPC response to competitive matches, demonstrating fatigue in the immediate post match assessments and 24-post assessment and recovery in the subsequent 48-72 hours (figure 7). Matinlauri et al., 2019 examined the reliability of a standing 90:20 test (figure 6, panel C) in semi-professional players, and compared the fatigue-recovery profile of the test (immediately post, +24h, and +48h) following a simulated football protocol with that of the supine 90:90.

Figure 7: IPC values in academy footballers following a competitive match.



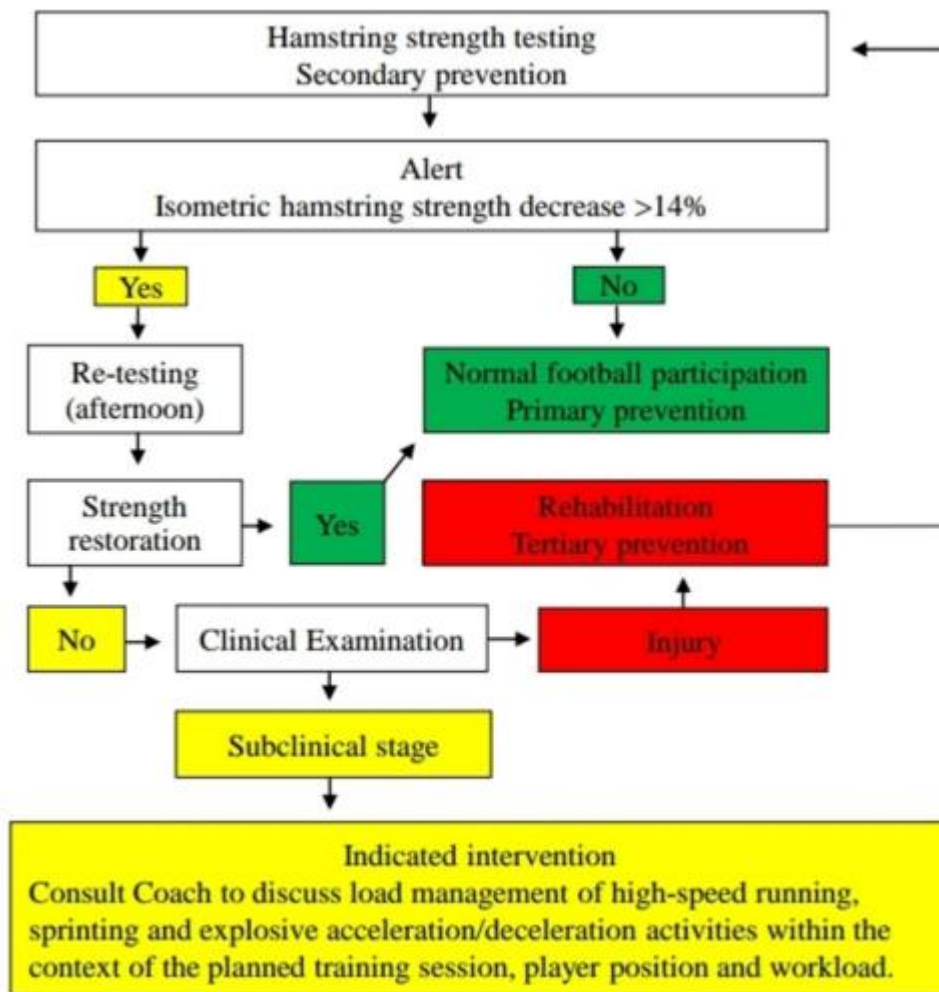
Source: Constantine et al. 2019 p5.

Values are mean of total (left and right limb) 90° and 30° supine bridge test values in 14 academy players. Pre=test performed prior to match; Post=test performed post; 24+, 48+ and 72+ after the match, respectively. Red bars indicate significant differences between timepoints.

Collectively these studies, and the author's experience in professional football, confirm the feasibility of integrating IPC testing into competitive micro-cycles without disrupting training, as they are generally well tolerated among professional players. The test has become well established in several English Premier League teams, and is for example a core element of matchday +2 monitoring at Arsenal Football Club (Arsenal SEMS conference, 2019).

Wollin et al. (2020) describe regular IPC monitoring of footballers as a model for secondary prevention of HSIs which includes repeat testing within the same day or consecutive days if anomalies are detected (figure 8).

Figure 8: Hamstring strength testing cycle.



Source: Wollin et al 2020. p1.

In the healthy athlete, IPC's are principally used in monitoring of short-term load response and week to week trends with use in profiling or comparisons between players or groups is less common. This may be partly due to the traditional interest in dynamic isokinetic hamstrings concentric or eccentric peak torque or peak torque (hamstring:quadriceps) ratios and the more recent widespread use of the NHE (i.e. Nordbord) for the purpose of "profiling" and classifying strength. This was stimulated by prospective evidence demonstrating that lower levels of NHE-eccentric strength peak force were associated with elevated HSI risk (Timmins et al., 2016; Bourne et al., 2015), the estimation of adequate NHE strength cut points and the ease of implementing the NHE test relative to isokinetic hamstring assessments. In addition, despite some evidence that lower isokinetic hamstring strength or high levels of interlimb strength asymmetry, or poor hamstring:quadricep peak torque ratios as identified in preseason strength screening, recent meta analysis and prospective studies have challenged the predictive value of these measures in HSI risk (Green et al., 2018).

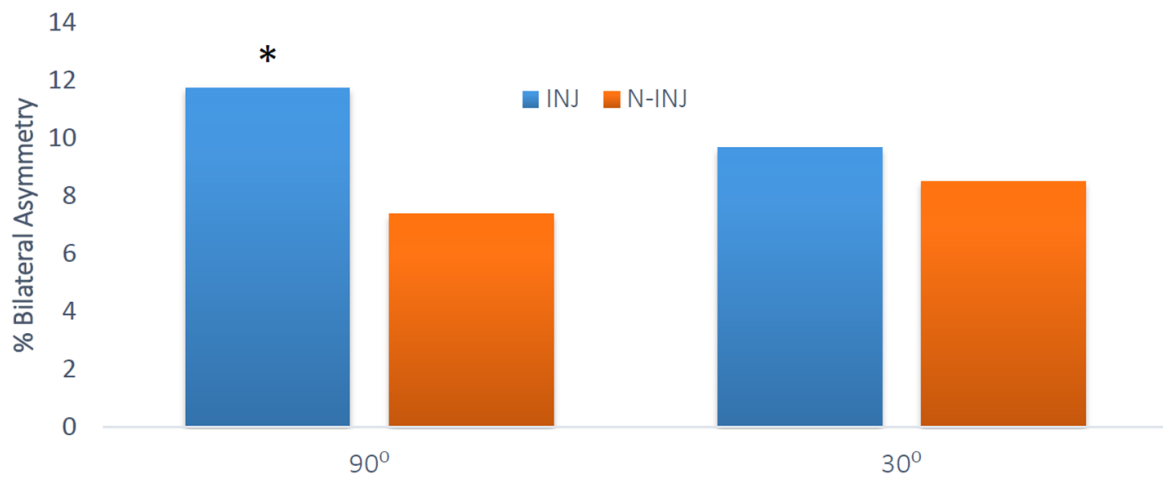
The theoretical basis for the importance of isometric strength within the sprint cycle and relevance of isometric strength and strength training in HSI risk reduction has been outlined by Van Hooren & Bosch (2017). However, to the author's knowledge, with the exception of a single study showing increased risk of injury recurrence associated with higher isometric peak force asymmetry determined in 15° knee flexion (De Vos et al., 2014) and a recent prospective risk study (Lahti et al., 2022), research examining isometric hamstring or posterior chain strength in relation to HSI associations is limited to retrospective evidence (Cohen et al, 2014; Charlton et al., 2018b; Buhmann et al., 2022). Furthermore, there is not yet evidence paralleling the studies showing that integrating eccentric hamstring strengthening exercises reduces HSI risk (Van Dyk et al., 2019; Chebbi et al., 2022). As such, neither cut points for adequate IPC strength associated with risk nor conclusive associations with HSI have yet to be established. On this basis, it is recommended that screening for low hamstring strength is done using the NHE, while the IPC tests allow complementary force assessment relevant to load-response in healthy and rehabilitating athletes.

Nonetheless, reference values for IPC peak force and descriptive data (mean and SD), can provide statistical cutpoints for low strength - the last module will have that data.

Retrospective data

Charlton et al. (2018b) examined associations between fixed dynamometer hamstring isometric peak force measures (peak force, peak torque, relative peak torque) and prior injury in a sample of 37 healthy male, semi-professional Aussie rules footballers, of which 10 (27%) had a history of HSI. History of HSI denoted not currently injured but with an HSI occurrence resulting in missed match-play, between one and three seasons prior to testing. Those with prior injury had values that were approximately 10-12% lower: peak force (-44.8 N, mean difference 10.3%), torque (-22.2 Nm, mean difference: -11.1%) and torque normalised to body mass (-0.2 Nm kg⁻¹, mean difference -12.5%). Torque (peak force*length of moment arm) relative to body mass, the measure that best distinguished injured versus non-injured. Similarly, Cohen et al., (2014), reported significantly larger interlimb asymmetries in the force platform 90° bridge in healthy elite footballers who had experienced at least one HSI in the previous season compared to those players who hadn't (figure 9).

Figure 9: Isometric Bilateral Peak Force Asymmetry in Relation to Previous Hamstrings Injury in Professional Footballers (n=31)



Sources: Prior Hamstrings Strain is Associated with Bilateral Isometric Strength Imbalance in Professional Footballers; by Cohen, D; Ashworth, B; Taberner, M; Evans, R; Lewin, C.; 2014.

INJ=Players with hamstring injury in the previous 2 seasons (n=8); N-INJ=Players with no hamstring injury in previous 2 seasons (n=23)

Players were tested at the IPC 90 and 30.

*Indicates a significant difference in % asymmetry between INJ and N-INJ $P < 0.05$.

Asymmetry significant higher in INJ vs N-INJ at 90° ($p=0.02$, $ES=0.83$, “large”) but not at 30° ($p=0.24$, $ES=0.28$ “small”).

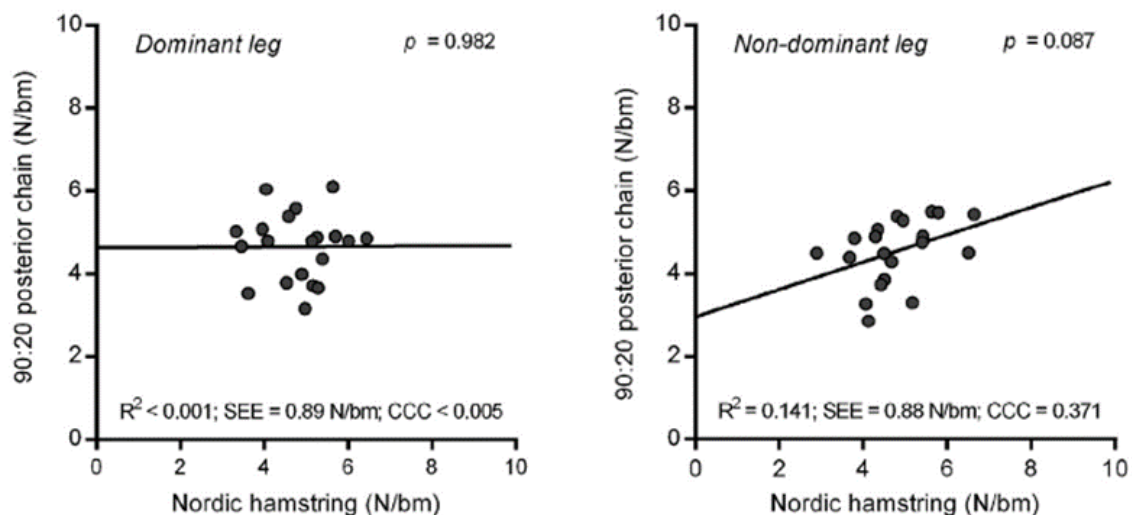
Only one prospective study has evaluated the association between IPC performance and prospective injury risk in athletes. This analysis of the association between performance in a four component (posterior chain strength, sprint mechanical output, lumbopelvic control, and range of motion), 11 item multicomponent screening protocol (Football Hamstring Screening, (Lahti et al., 2020)) and HSI risk in 95 professional footballers. Preseason differences between isometric peak force relative to body weight in the 2 unilateral, handheld dynamometer, isometric peak force tests in the 17 players who sustained injuries during the season and the 78 that didn't were trivial and non-significant. Isometric peak force asymmetries were higher (effect size: 0.32, *small*) in those that went on to sustain an injury 8.1% (CI: 5.4 to 10.8) than those that didn't 6.4% (CI: 5.3 to 7.5), but this difference was not significant ($p=0.22$). Despite the mechanistic basis for items included in the screening protocol, performance in no single item in isolation differentiated players who would or would not sustain an injury across the whole season, while lower horizontal force obtained during two 30-m maximal sprints estimated using a radar gun, was associated with a significant increase in risk of injury in the first part of season. Given the multifactorial nature of injury, these results are not unexpected - with the potential for specific risk factors being present and causal in a given player while other factors being pertinent to another player.

In the context of there being several prospective risk studies demonstrating the predictive value of the NHE - *where does IPC testing fit in?* Firstly, a poor agreement between NHE

performance and IPC peak force is reported - so the IPC cannot be said to be a proxy for NHE peak force. In 20 professional male footballers, Moreno-Pérez et al., 2020 measured NHE peak eccentric force measured with a strain gauge, handheld dynamometry assessment of isometric peak force @ 15 knee flexion and the 90:20 isometric posterior chain strength and observed poor associations between isometric and eccentric tests. There was poor agreement both in terms of absolute values obtained in each limb and asymmetries identified, highlighting for example: 30% of the players had NHE interlimb asymmetries >15%, 25% had > 15% in 15 knee flexion and 5% in the 90:20 test. The data of Moreno-Pérez et al., 2020 indicates that differing neuromuscular performance qualities are being characterised which are not closely associated with each other and cannot be used interchangeably. supporting the use of multiple strength tests during HSI rehabilitation with the inclusion of both isometric and eccentric assessments (Taberner et al., 2020).

Figure 10: Agreement between IPC and NHE tests in professional footballers

90:20 posterior chain vs. Nordic hamstring



Source: Moreno-Pérez et al., 2020

Linear relationship between force values in Nordic hamstring and 90:20 isometric posterior chain strength). SEE: Standard error of estimate. CCC: Lin's concordance correlation coefficient.

The IPC is however considered by many to be less invasive and of lower player demand or burden relative to both IKD and to NHE assessments. As such, particularly, during congested competition periods, which are associated with a higher incidence of muscle injury (Carling et al., 2016; Bengtsson et al., 2013) the IPC is a more acceptable means to obtain frequent (week to week for example) in-season. The IPC may also be more acceptable in early monitoring of hamstring early in rehabilitation, (Moreno-Pérez et al., 2020; Taberner 2022)

when eccentric exercise and evaluations are conventionally avoided on the basis of the potential for excessive mechanical load on the muscle.

Therefore the IPC provides a means to obtain objective neuromuscular performance data and identify **changes in force** which may reflect maladaptation and address or response to these changes and the potential to capture potential interactions between a player's response to the demands of individual match-play or accumulated matches and HSI risk and allow adjustments to be made to training/recovery schedules during the same day – as outlined by Wollin (2020 - figure 7). Regarding integration, it is important for the practitioner to also consider the evidence around the analgesic effects of isometric *training*, stimulus for tendon and muscle adaptations and potential preconditioning effect (Chen et al., 2018; Barreto et al., 2019) that might provide avenues to incorporate into training sessions.

Choice of IPC test

The force platform IPC protocols described (and handheld assessments (Lahti et al., 2021) involve differing knee and / or hip joint angles. Assessing at more than one angle may provide information gain due to alterations in the relative activation pattern and demands at each with both the 90, 30 Schache/McCall tests implemented in some environments (Nedelec et al, 2014; Arsenal FC SEMS conference, 2019). Direct and indirect comparisons of sensitivity are discussed below. However, as proposed with respect to jump testing, if practicable a preseason / periodic screening protocol/battery would be more thorough - and therefore might include more than one angle - whereas a protocol that is applied frequently during the season as part of a load-response monitoring program, particularly in the professional environment would endeavour to use minimum dose assessment. Yet, it is important to be aware that there are teams in elite football that have routinely implemented both 30° and 90° in weekly matchday +2 monitoring (Arsenal FC SEMS conference, 2019). While there is potential for additional information gained by comparing profiles at one time point or trends in performance across the 2 tests, for practical reasons a single IPC may be preferred and may be considered as adequate based on considerations outlined below in evidence related to fatigue-recovery monitoring. There may however be caveats to this, and as always, the practitioner should consider both the potential for information gain by adding tests but also the time cost, and the practicality and impact on athlete buy-in to repeat these tests, or whether more frequent insights with a single test should be prioritised. Situations in which information gain from additional tests to gain a more detailed profile of neuromuscular performance:

- An athlete with recurrent HSI's
- During rehab or following return from HSI
- During rehab or following return from ACL-R using hamstring graft to have
- An athlete involved in specific conditioning to develop hamstring/posterior chain performance

The question that the practitioner seeking to integrate a single IPC will ask: *which is the best IPC test to use?* The answer, in high-performance settings, will be based on a combination of evidence, practitioner experience, clinical reasoning and practical considerations. Taking into consideration the key performance and/or injury related questions and the practical limitations of their context, an understanding of between tests differences in the following will help inform the test(s) selection decision:

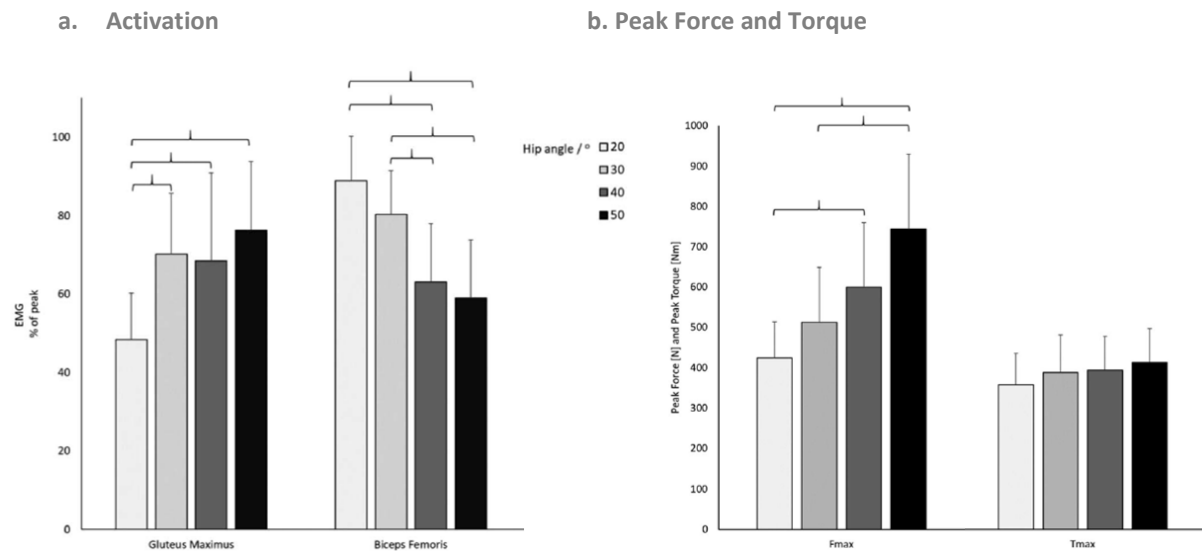
- the relative contribution of the posterior chain muscles involved
- reliability
- sensitivity (to load)

The availability/use of other assessment tools - such as the NHE - should also be considered.

Activation patterns

Variations in the angle of knee and hip have significant effects on activation patterns across posterior chain muscles (Onishi et al., 2002) and therefore their relative contribution to force production in posterior chain/hamstring tests. Note that unlike the open chain fixed and handheld dyna assessments, the force platform IPC test variants described above are closed chain tasks with the foot limb distally anchored. The latter allow greater hip extension force production and higher biceps femoris long head activation in comparison with open chain tasks (Bourne et al., 2016) and in the supine force platform tests (figure 6), hamstring recruitment greater when the leg is in a more extended position. The relative activation of the biceps femoris, gluteus maximus and other posterior chain muscles have been compared across the supine bridge tests (30° and 90°) and at various floor hip-bridge (or “hip thrust”) angles (Goodwin & Bull, 2021). The more lengthened position of the hamstrings in the 30° compared to the 90° and in the floor hip-bridge at 20° compared to greater knee flexion positions, allow more effective transfer of extension torque to the distal point of foot contact with the force platform than the gluteus maximus. In a study in 14 active males, Goodwin & Bull (2021) reported a progressive increase in biceps femoris and decrease in gluteus maximus recruitment across hip flexion angles of 50° to 20° in the floor Iso-hip-bridge, with values significantly lower at 20° (figure 11).

Figure 11: Isometric Floor Hip bridge at 4 different hip joint angles



Source: Adapted from Goodwin & Bull (2021). p6

a. % of maximum (surface) EMG in Gluteus Maximus and Biceps Femoris in 4 positions; mean of 3 trials at each angle normalised to the highest recorded value across all tests for the muscle being considered. Vastus lateralis activation (not shown) was also measured and did not significantly differ by joint angle. Brackets indicate significant *post hoc* paired differences. b. Force Platform measured: Max F = Peak Vertical Force; Max T = Peak Torque (Force * moment arm). Floor hip-bridge test shown in above in figure 6, panel D.

Read et al., (2019) compared activation in the 30° and 90° supine bridge tests (figure 6. Panel A, B) in 10 male recreational soccer players and found significantly higher biceps femoris activation at 30° (31 ± 9) than 90° (22 ± 7), representing a large effect size difference (1.19). Medial hamstring activation was also 15% higher in the 30° (ES: 0.40, “small”) but this difference was not significant.

Reliability

McCall et al., (2015) first reported reliability values for the force platform 90 and 30 supine bridge tests - in 29 professional male footballers. After two familiarisation sessions, interday CV's of 4.3% and 5.4% were observed in the dominant and non-dominant leg respectively in the 90° and 6.3% (dominant) and 4.8% (non-dominant) in the 30°. The smallest change in the mean values were observed in dominant leg 30°: 1.0 N (90%CI: -6.9 to -9.0) and the largest in the non-dominant limb, also in the 30°: -4.1 N (-9.9 to -1.7) (table 5). The ICC's and minimal detectable change (MDC) values are also shown for the two test positions. The MDC facilitates an estimate of the “minimal difference needed to be considered as real” for a given test and is calculated as the typical error (TE) * 1.96 * $\sqrt{2}$ (Weir, 2005).

Table 5: Interday reliability and measurement characteristics of peak force in supine bridge 90° and 30° force platform tests in male professional footballers (n=29)

	CV	TE (90% CL)	Change in mean (90% CL)	ICC (90% CL)	MD
Dominant leg at 90°	4.34%	9.4 N (7.3–13.6)	2.1 N (–3.8 to –7.9)	0.95 (0.88–0.98)	26.2
Non-dominant leg at 90°	5.48%	11.5 N (8.9–16.8)	–2.3 N (–9.7 to –5.1)	0.95 (0.88–0.98)	31.9
Dominant leg at 30°	6.31%	13.3 N (10.4–18.9)	1.0 N (–6.9 to –9.0)	0.86 (0.69–0.94)	36.9
Non-dominant leg at 30°	4.84%	9.7 N (7.6–13.7)	–4.1 N (–9.9 to –1.7)	0.93 (0.84–0.97)	26.8

CV=coefficient of variation; TE=typical error of measurement; ICC=intraclass correlation coefficient; MD=minimal difference. Test positions shown in figure 6 (a.b) above.

Source: McCall, A., Nedelec, M., Carling, C., Le Gall, F., Berthoin, S., & Dupont, G. (2015). Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional football players. *Journal of sports sciences*, 33(12), 1298–1304. <https://doi.org/10.1080/02640414.2015.1022579>

While these values indicate good-high reliability, Cuthbert et al., (2021) reported larger interday CV's and lower ICC's for the same tests in professional female footballers after 1 familiarisation session (table 6):

Table 6: Interday reliability of peak force in supine bridge 90° and 30° force platform tests in female professional footballers (n=23)

Test Position	Limb	CV (%)	ICC (95%CI)
30°	L	8.7	0.76 (0.29–0.82)
	R	6.5	0.86 (0.64–0.94)
90°	L	10.2	0.70 (0.27–0.87)
	R	7.5	0.80 (0.53–0.91)

Source: prepared by the author, adapted from Cuthbert et al; 2021

Relative to reliability of the 90° and 30° reported by McCall et al., (2015), lower interday reliability was also reported for the 90°:20°, evaluated in 24 semi-professional male footballers after 2 familiarisation sessions. The hands on chest protocol (figure 6, panel c) displaying CV's (95%CI) of 8.1% (5.3 to 10.9) and 7.3% (4.7 to 9.9) in dominant and non-dominant limbs, respectively. The greater variability in the 90°:20° is perhaps expected given the athlete is standing rather than supported and has more degrees of freedom and body segments to control, in that they have to stabilise at the trunk to apply force into the platforms.

Goodwin & Bull (2021) examined within-session and interday reliability of the floor isometric hip-bridge across 4 consecutive days. They reported combined (mean of 4 positions tested) within session CV's (across 3 trials) for peak force of 6.2% on the first day, 4.3 on the 2nd, 3.6 on the 3rd and 3.3% on the 4th, indicating a small improvement across days but an acceptable level of reliability on day 1. They also noted low inter-day variability of peak force in the bilateral, left and right tests, particularly after day 1; for example the change in the mean in the right limb peak force between day 1 and 2 was 0.37 (95%CI: 0.03 to 0.71) -0.05 (-0.37 to 0.27) between day 2 and 3 and 0.00 (-0.26 to 0.26) between day 3 and 4. Better values were observed for bilateral testing and for the right limb (which is generally the dominant limb); Left limb ICC was 0.60 (0.12 to 0.85) on 1st day vs 0.87 (0.66 to 0.96) on the right, left limb CV also stabilising one session later than on the right.

Based on high ICC values in 2 day assessment they concluded that for ranking-based assessment (i.e comparison across a team), peak values can be used without familiarization. However, based on absolute change in the mean, typical errors (CV), and changes across the pairs of test sessions, they suggested that familiarization is appropriate if the purpose of testing is the detection of meaningful change.

The EMG study of Read et al (2019), comparing the 30° and 90° did not measure force output, they did however report the reliability of activation across the muscle groups evaluated. They noted that while the interday reliability (CV) of biceps femoris activation was 13-14%, gluteus maximus recruitment had much higher variability, particularly within-subjects; 19% at 90° and 36% at 30°, representing poor reliability. While force wasn't measured, it is logical that these variations would influence force output. The authors suggest that the within-subject variability they observed was partly due to athlete interpretation of the test instruction to 'push' the heel into the box. Some athletes interpret push as emphasising hip extension dominant force production and will try to / succeed in lifting hips. As shown in figure 6 (a.b), the protocols involve practitioners applying pressure on the athlete's hip to try and ensure that the hip stays in contact with the floor during the contraction. Other athletes will follow the instruction to drive the heel into the box and with more of a knee flexion intent. Read et al suggests that these differing approaches to the task are an important contributor to the larger variations they observed in gluteal and gastrocnemius contributions. Medial gastrocnemius activation is likely to be influenced by ankle position, both in terms of rotation and degree of plantar or dorsiflexion. These aspects of the protocol should be well standardised, and familiarisation prior to testing will enable the practitioner to identify those athletes who need more precise or adjusted cues. As highlighted with respect to jump testing, from the monitoring perspective, consistency within athletes is prioritised over inter-athlete consistency.

Overall, while acceptable rank order reliability suggests that "profiling" of peak force could be implemented without familiarisation, for monitoring purposes - detecting meaningful change - 2-3 familiarisation sessions are recommended prior to confidently defining an athletes baseline. In practice, the high-performance context, familiarisation can be gained

with repeated weekly testing but the initial weeks values acquired should not be considered “true baselines”. Given that isometric training may also be a component of conditioning programs, practitioners may also begin to familiarise athletes with the task within training sessions - without setting up as an assessment. As part of familiarisation, the practitioner has the opportunity to evaluate and correct execution errors; in particular an over-emphasis on hip extension to ensure adequate flexion recruitment.

IPC-Rate of force development

As discussed above with respect to isometric extension tests, in addition to peak force, RFD is also of interest in these assessments. IPC force platform assessment is a novel phenomenon (McCall et al., 2015) relative to the more than 25 years of IMTP literature. With some exceptions (Taberner et al., 2018; Taberner et al., 2020; Taberner et al., 2022; Goodwin & Bull, 2021), studies involving IPC assessments have reported peak force but not RFD. Based on data from other isometric assessments, the reliability of RFD is expected to be lower than peak force, although to the authors knowledge there is only one published report of interday reliability of the IPC tests (Goodwin & Bull, 2021). The RFD measure examined in this study of the floor hip-bridge was torque @ 150ms (derived from force @ 150ms and which is equivalent to RFD @ 150 ms). Within session reliability improved from 16% to 13% across the 4 testing days but remained substantially higher than the 3.3% noted for peak force on day 4. In terms of interday reliability the ICC's on day one were identical to that of peak force (0.87), suggesting within group rank comparison might be made, but unlike for peak force, there were significant increases across the 4 days in bilateral and left limb values and non significant increases in the right limb. Overall, this study showed that while more familiarisation will be needed, force@/RFD is a viable metric in this test. Further work is needed to examine this in the other IPC tests in a high-performance setting with the associated challenges. It is the authors experience that within a group of athletes, there will be individuals who are with little familiarisation can for example produce reliable RFD outputs in the 90°, while others require substantially more coaching, or never do. Coaching and cues - with an emphasis not only a maximal but also a fast contraction, are more important. It also suggested that separate tests should be performed to evaluate peak force versus RFD - such that the RFD test would focus purely on rapid contraction and be a shorter 1 second test (Maffiuletti et al., 2016), whereas the current IPC protocols are 3 seconds, allowing development of force. Footwear / absence of it, also can impact on RFD measurements as the point of contact is the heel in these tests - with variations in the compressive qualities of the shoe material influencing outputs.

The use of RFD/potential information gain associated with it in the context of monitoring load-response in healthy athletes is discussed in module 3 of this course and in the context of rehabilitation in module 4.

Test sensitivity

The question as to whether one of the IPC protocols/positions described has superior sensitivity to the effects of real or simulated football matchplay is of interest from a test selection perspective and has been directly and indirectly examined in several studies. McCall's study examined the acute effect of competitive matches on IPC peak force - implementing the tests between 5 and 15 min following the end of the match - observed 11-16% (29 to 50 N) declines with no apparent position-specific difference. This information is important as it was the first to demonstrate the ability of these force platform isometric tests to detect acute match induced posterior chain/hamstring fatigue - which had been previously studied principally using far more time consuming, and difficult to access, isokinetic tests. However, in practice in high performance/professional settings it is more likely that these assessments would be performed matchday +1, +2 or +3 to define residual response/recovery.

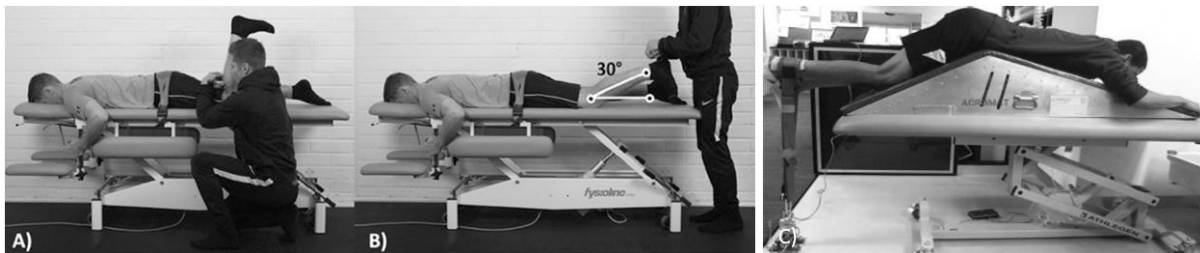
While in semi-professional players, Matinlauri et al., 2019 found similar patterns when comparing the fatigue-recovery profile of the 90°:20° and 90° following a 90 minute simulated match protocol, they did note that at +48h, the 90°:20° remained significantly below baseline in dominant and non-dominant limbs ($P < 0.01$, -13.0%) and non-dominant limbs ($P < 0.05$, -10.4%), while deficits were slightly smaller and non-significant for the 90° (dominant: -10.1%; non-dominant: -9.1%). For reference, their immediate post-protocol decreases were very similar to that reported by McCall immediately after a 90-minute competitive match (16% in dominant, 13% in non-dominant limbs, respectively). Although using a pressure cuff rather than a force platform, in professional players post competition Nedelec et al. (2014) noted a larger effect size for force loss in the 30° position than the 90° +48 and +72 hours. In youth academy players, Constantine et al. (2019) reported that while overall there was no significant interaction between angle and time course of recovery, deficits (relative to pre match values) were larger in the 30° than 90° at +24 (30°: -12.1% 90°: -3.1%) and +48 (30°: -3.4%, 90°: +3.1%) post competition.

Constantine et al. (2019) highlight an interesting pattern observed across the IPC fatigue recovery studies (force platform, fixed dynamometer and pressure cuff), was that in the studies with younger players largely showed recovery at 48h post-match or no significant difference versus pre match values whereas studies in senior players tend to show significant 8-10% deficits at this time point. This observation warrants confirmation in future work, but suggests that changes in fatigue response/a slower rate of recovery may already be apparent in players in their early-mid 20's compared to 16-18 year olds.

Given the emphasis on the health of the biceps femoris, as it is the most frequently injured posterior chain muscle, one of the key considerations in test selection is the relative involvement of the biceps femoris. It is evident that the more extended position assessments (30°, 90°:20°) relative to the 90°, both have the higher activation of this muscle and appear to

be more sensitive to match-induced fatigue at +48h/matchday + 2. On the other hand, the 90 is of these 3 tests, the simpler to set up and implement rapidly and on this basis should still be considered. The author's view is that with respect to monitoring it remains a practical tool. However, the floor based hip bridges, although not yet evaluated in terms of load-response, also show promise.

Figure 12: Handheld and Fixed Dynamometer Isometric Hamstring Tests



Source: Reliability of externally fixed dynamometry hamstring strength testing in elite youth football players; by Wollin M, Purdam C, Drew MK; 2016, *J Sci Med Sport*. 19(1):93–96. <https://doi.org/10.1016/j.jsams.2015.01.012> PMID: 25683733

Handheld dynamometry assessments of A) knee flexion @ 90 and B) Knee flexion @ 30 (Lahti et al., 2020) C) Fixed dynamometer

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