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The Reliability of Countermovement Jump Performance and the Reactive Strength Index in Identifying Drop-Jump Drop Height in Hurling Players

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Abstract

The purpose of this study was to estimate the inter-day reliability of countermovement jump performance (CMJ) and the reactive strength index (RSI) in identifying drop-jump drop height in male hurling players. Eighteen male hurling players volunteered to participate. Subjects performed the CMJ and drop-jump test for RSI during the same sessions on three separate occasions a minimum of 48 hours apart. Subjects performed three CMJs and two drop-jumps from five different heights in an incremental manner (0.20, 0.30, 0.40, 0.50, 0.60 m). The results displayed acceptable levels of relative and absolute reliability for the following CMJ measures: height, velocity, force, power and average eccentric rate of force development measures (RFD). Absolute and relative peak concentric rate of force development from the CMJ test were found to have low levels of absolute reliability due to high CV% values. RSI and identified drop height from the drop-jump test displayed acceptable reliability (ICC single measure = 0.88 and 0.92 respectively; CV% = 6% and 10% respectively). Furthermore, limits of agreement random error displayed acceptable reliability for CMJ and drop-jump measures from estimated feasible minimum *a priori* sample sizes based upon limits of agreement. In conclusion, CMJ force-time measures (excluding peak concentric RFD measures), RSI and the identified drop height have acceptable absolute and relative reliability. For the sport science practitioner involved in hurling and for hurling players, this means that the CMJ test is reliable for kinetic and kinematic variables and the drop-jump test provides a means of developing a reactive strength profile and a means of individualizing drop height for drop-jump training.

Keywords: Reliability; Countermovement jump; Drop-Jump; Reactive strength; Hurling

Introduction

The field sport of hurling is a national sport in Ireland where two teams of 15 male players play for a total of 70 minutes on a pitch 40% longer in length than a soccer pitch [1]. Hurling is unique to other field sports as the play can change rapidly from one end of the pitch to the other due to the large distances the ball can travel after been struck with a hurley (wooden stick used in the game) and requires players to contest for possession aerially or on the pitch surface [1]. These game demands require hurling players to have the ability to jump and catch the ball in offensive and defensive situations alongside completing high speed running or sprint accelerations [2]. This ability to accelerate over distances up to approximately 20 m in offensive and defensive situations is essential as accelerations occur close to the ball and can determine the outcome of key events during the game [1]. To assess the jumping and reactive strength abilities, it is necessary to have reliable tests available for the sport science practitioner specific to this type of field sport. To date, a lack of research exists in estimating the reliability of athletic performance tests for jumping performance and reactive strength in male hurling players.

Previous research has examined the relationships between the ability to accelerate over distances of 10 and 20 m, reactive strength and countermovement jump (CMJ) height [3, 4]. Cunningham et al. [3] reported that significant relationships existed between 10 m sprint time and CMJ height (r = -0.88) and reactive strength index (RSI) (r = -0.60) in rugby union players. To highlight the importance of CMJ height, Shalfawi et al. [4] reported significant relationships between CMJ height and 10 m time (r = 0.45) and CMJ height and 20 m time (r = 0.49) in professional basketball players. The evidence of these strong relationships justifies the need to assess the reliability of CMJ and RSI tests as they can predict the impact of jump training on sprint performance on hurling players and other similar field sports.

The CMJ test is a valuable lower limb test and is a means of assessing a number of force-time measures using a force plate [5]. Previous studies have investigated the reliability of a number of intra-day and inter-day measures that can be obtained from the CMJ [5-7]. Cormack et al. [6] reported peak and mean measures of force and power (absolute and relative measures) to be reliable intraday (CV<7.0%). Furthermore, the other intraday studies reported force (mean [5] and peak [5,7]) and peak and mean power [5,7] to be reliable (ICC > 0.84; CV < 8.0%). Height [6,7] and velocity (mean and peak) [5] were reported to be reliable intra-day (ICC > 0.84; CV < 8.0%). Two of the studies [5,7] used males actively participating in recreational level sport whereas Cormack et al. [6] used elite Australian rules footballers. When considering the inter-day estimation of reliability, Cormack et al. [6] showed that CMJ height, force and power measures (peak and mean values for force and power) were reliable (CV < 6.0%). However, the rate of force development (RFD) has shown mixed findings [5,7] to date for reliability, based on the intraclass correlation coefficient (ICC), and questionable levels of reliability based on coefficients of variation (CV). Hori et al. [5] found concentric peak RFD did not meet their ICC reliability requirements at force plate sampling frequencies at 100 Hz and above (ICC = 0.66; CV% = 23.5%) with university students that were physically active. Furthermore, McLellan et al. [7] tested males involved in recreational field sports and reported that concentric peak and average RFD, when used as a measure of CMJ performance, should be used with caution due to its low level of reliability (ICC = 0.89; CV% = 14.8 -16.9%). However, Laffaye et al. [8] reported high ICCs (0.92–0.95) for force variables which included absolute and relative eccentric RFD for elite male and female athletes involved in field and court sports.

Reactive strength has been defined as the ability of the neuromuscular system to tolerate a relatively high stretch load and change from a rapid eccentric muscle action to a rapid concentric muscle action [9]. The RSI can be assessed using a drop-jump test from a variety of heights using a bounce technique (bounce drop-jump (BDJ) where ground contact time is kept to a minimum, with a maximum cut-off of 0.250 s targeting the fast stretch-shortening cycle (SSC) and also aiming to achieve maximum height [10]. The test protocol is used to measure an athlete's reactive strength capability, which underpins their ability to jump and sprint. The drop-jump test applying the RSI protocol, can be used to monitor an athlete's reactive strength capability as well as to determine the drop height for drop-jump training [11]. Intra-day drop-jump reliability has been previously investigated [14, 19]. Drop-jump height, ground contact time and RSI when tested using a force plate from a 0.30 m drop height have been found to have high levels of reliability [12]. Reliability in this study was based upon Cronbach's alpha (> 0.95) and ICC single and average measures for the three measures (> 0.9). A second study by Marwick et al. [13] found RSI to be reliable across a number of drop heights for professional basketball players (0.20, 0.40 and 0.50 m) [ICC > 0.89, CV% < 8%]. Non-significant differences (P > 0.05) were found between the three trials for RSI at all of the drop heights. To date few studies have examined inter-day reliability of drop-jump measures such as jump height, ground contact time and RSI. One study to date assessed intra-day and inter-day reliability of jump height, ground contact time and RSI using elite rugby players on a contact mat [14]. This study showed acceptable levels of inter-trial reliability for ground contact time and RSI from a 0.40 m drop height (ICC > 0.85; CV% < 8.0%). Furthermore, acceptable levels of inter-day reliability were found for jump height, ground contact time and RSI at the same drop height (ICC > 0.84; CV% < 9%). CV% in this study was based upon a calculation of within subject variation.

Another important component of assessing drop-jumps is to be able to use jump height and reactive strength measures as a means to identify drop height for drop-jump training. To date, two studies [15,16] have investigated the reliability of a method to identify drop-jump drop height. Arteaga et al. [15] reported acceptable reliability for BDJ height and the identification of drop height from the corresponding maximum jump height value. Byrne et al. [16] investigated the reliability of RSI and its ability to identify optimal drop height in trained hurlers. This study reported high levels of inter-day reliability for RSI (ICC = 0.87; CV% = 4.3%) and optimal drop height (ICC = 0.81; CV% = 3.0%) over two test sessions. To date, a lack of studies exist in examining the reliability of the RSI to determine drop height and the reliability of the drop height identified for drop-jump training. The purpose of the current study was to estimate the test-retest reliability of a number of measures from the CMJ test and measures from a BDJ test where RSI was used to identify drop height for drop-jumping.

Materials and Methods

Subjects

Eighteen male hurling players (age (mean ± SD): 21.2 ± 2.1 years; mass: 79.2 ± 6.5 kg; height: 179.5 ± 3.7 cm) competing in the Irish collegiate league season and at club level, volunteered to participate in this study during the in-season. Subjects were hurling training on average three times per week and playing a match once per week. Subjects were also involved in weight training on average twice per week. Subjects had a minimum of one year's weight training experience. All subjects were encouraged to undertake their normal training during the studies. Subjects' had no orthopedic or musculoskeletal injuries to the lower extremities in the previous six months for both studies. Written consent to participate in the study was obtained from all subject in accordance with the Declaration of Helsinki. Ethical approval was provided by the institutional ethics committee.

Experimental design

This study aimed to estimate the inter-day reliability of a number of force-time measures from the CMJ test and the BDJ test in male hurling players. The reliability of RSI, jump height and ground contact time was estimated from the BDJ test. Furthermore, the reliable estimation of identifying drop height from the highest RSI was also considered. To estimate inter-day reliability, a test-retest research design was employed where three repeated trials were performed by each player a minimum of 48 hours and a maximum of 168 hours apart. At each test session, the CMJ test was performed first after performing a warm-up which comprised of three jumps. The BDJ test followed the CMJ test and used an incremental protocol over five heights (0.20, 0.30, 0.40, 0.50 and 0.60 m) to measure the highest RSI to identify the individual drop height for each subject. An incremental protocol was used so that the stretch load (intensity) would be progressively increased. The potential for order effects was considered non-significant as familiarization of the BDJs was provided and two minutes of rest was provided between drop heights to minimize fatigue [17].

Procedures

Subjects were familiarized with the testing and training procedures during one familiarization session. At this time, subjects were shown the CMJ and BDJ testing protocols. The first of the three repeated inter-day trials commenced within one week of the familiarization session. To account for diurnal variations subjects were tested at the same time of day (between 2-4pm) and all testing took place indoors. Subjects were required to wear the same footwear for all tests. A dynamic warm-up was used before the commencement of testing at each test session. The warm-up comprised of five minutes of self-paced low intensity jogging followed by five dynamic stretches targeting the gluteals, hamstrings, adductors, quadriceps and gastrocnemius [18]. These dynamic stretches were performed in the order stated, with two sets of fourteen repetitions completed on both legs over 10 meters [18]. After the completion of the warm-up, subjects commenced the CMJ test which was followed by the determination of maximum RSI to identify drop height after a 5 minute recovery period. These tests were performed over three test sessions, a minimum of 2 days and a maximum of 7 days apart.

Countermovement jump (CMJ) testing

Subjects were required to perform three countermovement jumps by squatting to a self-selected depth and then jumping upward for maximum height. Subjects were required to take-off and land on a portable force plate (Type 92886AA, Kistler Instruments Ltd, Hook, United Kingdom) . Hands were placed on the hips for the entire jump movement. A fifteen second recovery period was provided between jumps [19]. The best trial from the three trials was used for analysis. Scores were recorded as the trial that produced the highest height in meters.

Reactive strength index (RSI) testing and drop height determination

Subjects performed a drop-jump test to determine their highest RSI which was then used to identify drop height for drop-jumping. Subjects were provided with two practice jumps from each drop height before two jumps for measurement. Two drop-jumps from five different drop heights were performed (0.20, 0.30, 0.40, 0.50 and 0.60 m) using an incremental protocol. The recovery time period used between CMJs was also used between drop jumps across all the heights, with a two minute recovery period used between practice jumps and test jumps and between drop heights. The best RSI of two jumps for each drop height was used for analysis. Drop height was determined by employing the RSI method [11]. The RSI method identifies the drop height to be used as the height that produces the maximum RSI. Objectively, the ground contact time for each depth-jump has to be less than 0.25 s [10].

Data analysis for CMJ, reactive strength testing and drop height determination

A portable multi-component force plate with a built-in charge amplifier (Type 92886AA, Kistler Instruments Ltd, Hook, United Kingdom) was used to measure force-time measures at a sampling frequency of 1000 Hz and data was saved and analyzed using BTS-SMART software, using a tailor-made protocol (BTS Spa, Milan, Italy).

The measures of jump height, peak velocity, peak force, peak power, eccentric rate of force development and concentric rate of force development were calculated from the CMJ test data. All measures were calculated as absolute and relative values except for jump height and peak velocity. Relative values were calculated relative to body mass (kg).

Peak force was the highest ground reaction force in the vertical component during the concentric phase of the jump. Peak power was calculated from the product of peak force and peak velocity of the center of mass from the CMJ. To calculate peak velocity, center of mass velocity was derived from the numerical integration of vertical acceleration. Vertical acceleration was calculated by dividing the vertical ground reaction force by the subject's body mass. Concentric rate of force development was calculated as the difference in the peak ground reaction force and the start of the positive acceleration phase divided by the time from the force-time curve [20]. Eccentric rate of force development was calculated during the eccentric phase of the countermovement jump from the force-time curve when force exceeded body weight (N) and ended when velocity was equal to zero (bottom of descent before moving in an upward direction towards take-off) [8].

Jump height was calculated from flight time using the following equation [21]:

$$H = (g \times t^2)/8$$

Where: H = jump height (m); g = gravity (9.81 $m.s^{-2}$); t = flight time (s).

Drop-jump height was calculated using the equation above. Ground contact time during the amortization phase (the time frame when a subject is in contact with the ground before the subsequent jump) was calculated as the time between initial foot contact and take-off [12]. The reactive strength index (RSI) was calculated based on the equation:

$$RSI = \text{jump height (m)} / \text{contact time (s)}$$

Statistical Analyses

Means and standard deviations were calculated for all measures. A repeated measures analysis of variance (ANOVA RM) was used to identify systematic bias (e.g. fatigue or learning effect) between trials for each measure. Pair-wise post-hoc tests using a Dunn-Sidak adjustment were conducted to show significant pairwise differences for CMJ peak velocity only between trials two and three. Relative reliability was assessed using an intraclass correlation coefficient (ICC 3.1, 2-way mixed model with consistency and single effect measure [22]) and 95% confidence intervals. Average measures from this ICC model and Cronbach's alpha were also reported to be able to compare with reported ICC average and Cronbach's alpha values from previous work. Absolute reliability was assessed using Bland and Altman's 95% limits of agreement (LOA), coefficient of variance (CV%) and standard error of measurement (SEM). Random error of the LOA was determined ($s = \sqrt{(2 \times s\omega 2)}$ for all measures except CMJ peak velocity [23]. CMJ peak velocity random error was calculated by multiplying the SD of the mean of the differences between test session 1 (test) and test session 2 (retest) by 1.96. LOA random error of the measures was used to estimate the feasible minimum sample size for ANOVA RM. Estimated feasible minimum sample sizes were calculated for an ANOVA RM using G*Power software (Version 3.1.7, University of Kiel, Germany). Effect size for ANOVA RM in G*Power software was calculated using LOA random error of the measures and previous research with power and alpha levels set at 0.8 and 0.05 respectively. The SEM for all measures except peak velocity was calculated as follows: $SEM = 1.96 \times \sqrt{MSE}$ [24]. SEM for peak velocity was calculated as follows: $SEM = SD \times \sqrt{(1-ICC)}$ [25]. The CV was calculated as a percentage: CV% = (within-subject SD / mean) x 100 [4]. The first criterion for acceptable relative reliability was for the ICC single measure to achieve a value of ≥ 0.70 [26]. The second criterion for absolute reliability was to judge if the CV% was acceptable in terms of its usefulness for sport science practitioners with regards within subject variability. The third criterion for absolute reliability was for the authors to judge if LOA random error estimated minimum sample sizes to be feasible in magnitude. The tests / measures estimated acceptable reliability when the three criteria were met. A statistical significance of $P < 0.05$ applied throughout the analyses and statistical analyses were conducted using Minitab version 17 (Minitab Ltd, Pennsylvania State University, State College, Pennsylvania) and Statistical Package for Social Sciences version 20 (SPSS Inc., Chicago, Illinois).

Results

ANOVA RM showed systematic error ($P < 0.05$) for CMJ peak velocity only. As a consequence the third trial was discarded for analysis. Measures from the CMJ and BDJ tests displayed acceptable levels of relative reliability (ICCs) by meeting the criteria of greater than or equal to 0.70 (2). ICC (single and average measures), Cronbach's alpha and ICC 95% confidence intervals for measures related to the CMJ test and BDJ test are displayed in Tables 1 and 3 respectively. CV values suggested acceptable levels of absolute reliability and were equal to or less than 10% for the majority of the measures from the CMJ and BDJ tests except for the absolute and relative ECC-RFD and CON-RFD measures. These measures ranged from 14% to 40% for CV% (see Table 2). Tables 2 and 4 display three trial data for SEM, CV% and absolute LOA for the CMJ and BDJ tests.

Estimation of sample size for the CMJ and BDJ measures are displayed in Table 5. The measures for both tests estimated feasible minimum sample sizes when using LOAs to estimate the sample sizes from effect variances gathered from previous work [8, 11, 20, 27-30].

		ICC			
Measures	**Cronbach's α**	**Single measure**	**95% CI**	**Average measure**	**95% CI**
Height (m)	0.95	0.87	0.70 - 0.96	0.95	0.88 – 0.99
Peak velocity (m s^{-1})	0.94	0.83	0.63 – 0.94	0.94	0.84 – 0.98
Peak force (N)	0.94	0.84	0.65 – 0.94	0.94	0.85 – 0.98
Relative peak force (N kg^{-1})	0.91	0.76	0.52 – 0.91	0.91	0.76 – 0.97
Peak power (W)	0.95	0.87	0.72 – 0.96	0.95	0.88 – 0.99
Relative peak power (W kg^{-1})	0.96	0.88	0.74 – 0.96	0.96	0.89 – 0.99
ECC-RFD (N s^{-1})	0.96	0.88	0.74 – 0.96	0.96	0.90 – 0.99
Relative ECC-RFD (N kg^{-1})	0.95	0.86	0.70 – 0.95	0.95	0.87 – 0.98
CON-RFD (N s^{-1})	0.95	0.86	0.67 – 0.96	0.95	0.86 – 0.99
Relative CON-RFD (N kg^{-1})	0.95	0.87	0.69 – 0.96	0.95	0.87 - 0.99

ECC-RFD (N s^{-1}): Absolute eccentric rate of force development; ECC-RFD (N kg^{-1}): Relative eccentric rate of force development; CON-RFD (N s^{-1}): Absolute concentric rate of force development; CON-RFD (N kg^{-1}): Relative concentric rate of force development.

Table 1. Intraclass correlation coefficients (3.1, 2-way mixed model with consistency and single and average measures), 95% confidence intervals (CI) and Cronbach's alpha for CMJ measures.

Measures	**Trial 1**	**Trial 2**	**Trial 3**	**SEM**	**CV (%)**	**95% LOA**
Height (m)	0.36 ± 0.05	0.35 ± 0.05	0.34 ± 0.05	0.04	5.48	-0.007 ± 0.05
Peak velocity (m kg^{-1})	2.84 ± 0.33	2.88 ± 0.47	2.73 ± 0.42	0.33	6.09	0.04 ± 0.94
Peak force (N)	1727 ± 183	1698 ± 170	1717 ± 217	150.24	3.38	2.3 ± 212.47
Peak force (N kg^{-1})	23.0 ± 2.10	22.8 ± 1.60	23.0 ± 2.50	1.80	3.20	0.2 ± 2.60
Peak power (W)	4927 ± 957	4912 ± 1024	4734 ± 1320	805.35	7.75	59 ± 1138.94
Peak power (W kg^{-1})	64.37 ± 13.32	64.85 ± 14.53	62.97 ± 18.26	10.38	7.56	1.15 ± 14.68
ECC – RFD (N s^{-1})	4334 ± 2201	4313 ± 2170	4333 ± 2043	1364.16	14.33	-10.2 ± 1929.21
ECC-RFD (N kg^{-1})	52.6 ± 24.0	50.4 ± 21.0	53.9 ± 26.6	20.60	15.00	1.5 ± 29.20
CON-RFD (N s^{-1})	1515 ± 1358	1558 ± 1276	1320 ± 1340	800.93	33.80	55 ± 1132.70
CON-RFD (N kg^{-1})	20.9 ± 20.0	21.1 ± 18.0	18.3 ± 19.2	13.80	40.70	-0.8 ± 19.60

RFD (N s^{-1}): Absolute eccentric rate of force development; ECC-RFD (N kg^{-1}): Relative eccentric rate of force development; CON-RFD (N s^{-1}): Absolute concentric rate of force development; CON-RFD (N kg^{-1}): Relative concentric rate of force development.

Table 2. Three trial data for CMJ measures and standard error of measurement (SEM), coefficient of variance (CV%) and 95% limits of agreement (LOA).

	ICC				
Measures	**Cronbach's α**	**ICC single measure**	**(95% CI)**	**Average measure**	**95% CI**
Drop height (m)	0.97	0.92	0.93 – 0.99	0.97	0.92 – 0.99
Reactive strength index (m s^{-1})	0.94	0.85	0.66 – 0.95	0.94	0.83 – 0.98
Jump height (m)	0.87	0.70	0.38 – 0.90	0.87	0.65 – 0.96
Ground contact time (s)	0.88	0.71	0.40 – 0.90	0.88	0.66 – 0.96

Table 3. Intraclass correlation coefficients (3.1, 2-way mixed model with consistency and single and average measures), 95% confidence intervals (CI) and Cronbach's alpha for BDJ measures.

Measures	Trial 1	Trial 2	Trial 3	SEM	CV (%)	95% LOA
Drop height (m)	0.28 ± 0.06	0.27 ± 0.06	0.27 ± 0.06	0.05	6.50	-1.7 ± 0.04
RSI (m s^{-1})	1.15 ± 0.33	1.20 ± 0.38	1.18 ± 0.52	0.27	10.00	0.009 ± 0.2
Jump height (m)	0.23 ± 0.04	0.24 ± 0.04	0.22 ± 0.06	0.05	9.54	0.5 ± 0.03
Contact time (s)	0.195 ± 0.029	0.194 ± 0.027	0.184 ± 0.021	0.02	8.05	0.003 ± 0.02

Table 4. Ihree trial data for DJ measures and standard error of measurement (SEM), coefficient of variance (CV%) and absolute 95% limits of agreement (LOA).

Measure	Sample size (*n*)	Measure	Sample size (*n*)
CMJ		BDJ	
Height (cm)	14	Drop height (m)	6
Peak velocity (m s^{-1})	55	RSI (m/s)	13
Peak force (N)	12	Jump height (m)	11
Peak force (N kg^{-1})	12	Contact time (s)	10
Peak power (W)	30		
Peak power (W kg^{-1})	24		
ECC – RFD (N s^{-1})	12		
ECC-RFD (N kg^{-1})	17		
CON-RFD (N s^{-1})	13		
CON-RFD (N kg^{-1})	18		

ECC-RFD (N s^{-1}): Absolute eccentric rate of force development; ECC-RFD (N kg^{-1}): Relative eccentric rate of force development;
CON-RFD (N kg^{-1}): Absolute concentric rate of force development; CON-RFD (N kg^{-1}): Relative concentric rate of force development.
Table 5. Estimation of minimum a priori sample size for a repeated measures ANOVA for CMJ and BDJ measures using G*Power from LOAs and previous work (7, 8, 9, 13, 17, 18, 19).

Discussion

The current study is the first to attempt to estimate the test-retest reliability of CMJ measures and BDJ measures in male hurling players competing at collegiate and club level. The CMJ and BDJ test measures collected during the current study assessing male hurling players were found to have acceptable reliability except for absolute and relative peak concentric RFD. The judgment that concentric RFD measures had low reliability was based upon the high CV%s despite acceptable relative reliability and acceptable sample size estimation. Sample sizes estimated for ANOVA RM using G*Power were found to be of a minimal value that would be feasible in recruiting subjects when meeting a power of 0.8 for the measures collected from both the CMJ and BDJ tests and estimating acceptable reliability. When examining relative reliability based upon the ICC (3.1, single measure, average measure and Cronbach's alpha), CMJ and BDJ measures were found to have acceptable levels of relative reliability. This was based upon a rationale that these ICC values should be ≥ 0.70 as a minimum acceptable level of reliability [26]. ICC average measures and Cronbach's alpha were included so that comparisons could be made to indices gathered from previous studies. When examining the CV%, CMJ measures (except for absolute and relative measures of ECC-RFD and CON-RFD) and BDJ test measures were ≤ 10%. Absolute and relative ECC-RFD had a CV% of 14% and 15% respectively. Despite these CV% for ECC-RFD, the authors judged these CV%s to estimate acceptable absolute reliability in conjunction with acceptable absolute and relative reliability due to feasible minimum sample size estimation [24] and ICC values. However CON-RFD measures (absolute and relative measures) recorded CV% values between 30 and 40%. These CV% were judged to have low reliability in terms of within-subject variability and results in these measures been considered impractical for sport science practitioners wanting to determine the impact of training as an example. These four measures showed that when using the random error from the LOAs, a feasible minimum *a priori* sample size for ANOVA RM can be estimated to detect a significant change. The balance of measures from the CMJ and BDJ test displayed a feasible minimum *a priori* sample size estimations, based upon LOA random error. Therefore hurling players can be reliably assessed using the CMJ and BDJ tests in both a practical and research based setting except for absolute and relative peak concentric RFD. In terms of the BDJ test, the highest RSI and the identified drop height (from the highest RSI) were the key measures. Jump height and contact time were additional measures. The importance of measuring and monitoring CMJ height and RSI has been shown previously [3,4] by the strong relationships existing between CMJ height and sprint performance over 10 and 20 m and the relationship between RSI and 10 m sprint performance. The estimation of reliability in terms of measurement error for these measures provides a means of knowing when conditioning has had a positive effect above that of the error in the test, when assessing male hurling players.

Previous work [5-8] on CMJ reliability using a force plate has used both intra-day and inter-day experimental designs and the results of previous studies are comparable to those reported in the current study for ICC and CV% (see Tables 1 and 2). Comparable reliability between previous work and the current study shows that hurling players perform the CMJ test in a similar manner to other team sports, with participants competing at varying levels of competition. Cormac et al. [6] examined intra-day and inter-day reliability for a number of variables in elite Australian football males. They reported that all variables were below less than 7% for CV% for both intra-day and inter-day. Two other studies [5,7] examined intra-day reliability using ICC and CV% in males involved in sport. Hori et al. [5] reported that all variables measured from force-time data were reliable at a range of sampling frequencies, except for peak RFD (ICC > 0.7 and CV% < 12.0%). McLellan et al. [7] reported that force-time data was reliable (ICC > 0.89 and CV% < 4.0%) but stated that peak RFD data needed to be interpreted with caution due to its low test-retest reliability (ICC = 0.89 and CV% 16%). Laffaye et al. [8] has shown that average ECC-RFD to be reliable based upon an ICC of 0.95 only and this ICC is comparable to our ICC values. Previous studies did not report LOA so it is not possible to make comparisons to the current study. However, when examining SEM, the current study reports values that are not comparable to another study undertaken with elite Australian footballers [6]. Possible reasons are the differences in competition level, type and volume of training undertaken when comparing hurling players in this study, who were competing at club and college level versus elite level football players.

The findings of the present study when assessing male hurling players with respect to the measures for the BDJ test compared favorably with those from previous studies where subjects assessed were from field sports namely hurling and rugby. As this was the first study to report LOA for BDJ test measures, it was not possible to make comparisons to the literature. When considering SEM, a previous study [13] that assessed professional male basketball players reported a lower SEM for a number of drop heights in comparison to the current study. Highest RSI estimated acceptable levels of reliability (ICC single measure = 0.85; ICCα = 0.94; SEM = 0.27 m; CV% = 10%; LOA = 0.009 ± 0.2 ms^{-1}). The identified drop height from the highest RSI estimated acceptable levels of reliability (ICC single measure = 0.92; ICCα = 0.97; SEM = 0.05 m; CV% = 6.5%; LOA = -1.7 ± 0.04 m). Beattie and Flanagan [14] showed an acceptable level of inter-day reliability for RSI at a 0.40 m drop height (ICCα = 0.93; CV% = 8%). Arteaga et al. [15] showed that jump height and the identified drop height were reliable when performing a BDJ test (jump height CV% pooled = 6.2% and drop height CV%pooled = 31.9%). To the best of our knowledge, one study has been conducted using trained male hurlers that has found such high levels of inter-day reliability for RSI (ICC = 0.87; CV% = 4.2%) and optimal drop height (ICC = 0.81; CV% = 3.0%) using an incremental drop height protocol over two test sessions as those identified in the present study [16].

When compared to results from previous studies [12, 13] that examined intra-day reliability, the current study assessing male hurling players compares favorably, despite the inter-day reliability being examined. Flanagan et al. [12] tested college track and field athletes at a drop height of 0.30 m and found acceptable levels of reliability based upon ICC (RSI, jump height and contact time > 0.90). Marwick et al. [13] examined four drop heights from 0.20 m to 0.50 m in 0.10 m increments in terms of RSI and jump height. These researchers concluded that a single trial is viable to measure RSI from 0.20, 0.40 and 0.50 m drop heights in professional basketball players. This suggests that hurling players have the ability to reproduce a BDJ repeatedly inter-day and highlights the similarity between track and field and basketball and hurling, in the ability to be able to jump and sprint.

The acceptable levels of absolute and relative reliability for the CMJ test in this study may be attributed to male hurling players having experience of performing vertical jumps in a competition setting and the standardization of the protocol. Furthermore, the use of a familiarization session was of benefit to enable the subjects to become orientated with the protocol that was employed. However, the concentric peak RFD measures was judged to have low reliability due to high within-subject and this may be due to the varied technique employed by hurling players. Due to varying levels of coaching and experience in performing a CMJ or vertical jump, a variety of techniques were employed by male hurling players to achieve peak force in the shortest possible time. This is evident in the CV%s especially in relation to CON-RFD. The CV% in ECC-RFD was 14% which is similar to values reported in previous studies [16, 20]. It has been suggested that RFD and muscular strength play a greater role in the performance of a VJ than that of familiarization, co-ordination or any motor learning effect [15, 31]. As RFD is critical in maximizing jump performance, coaching of jumping should be part of hurling conditioning to optimize the hurling player's ability to jump and sprint in match situations.

The reliable measurement of the highest RSI and the identified training drop height for BDJ as found in the current study can be attributed to a standardized protocol and consistent coaching instructions [32]. Male hurling players were provided with a single familiarization session where coaching cues were provided and made clear thus ensuring that correct BDJ technique was achieved. The technique was achieved by enforcing the ground contact time of < 0.250 s and using a coaching cue of maximizing jump height and minimizing contact time. Previous work [12,13] supports the use of a single trial, in the current study two trials were provided at each height to monitor consistency of jumps at each height. From our experience, we would support the use of a single trial at each drop height when assessing RSI. This approach is valuable as the execution of the BDJ technique needs to be performed over incremental heights as it provides an indication of the reactive strength profile of the hurling player. Reactive strength which is assessed by means of the RSI is the ability of an individual to switch from a rapid eccentric muscle action to a rapid concentric muscle action when employing a fast stretch-shortening cycle where the amortization phase lasts < 0.250 s [10, 33]. The use of a BDJ test is specific for reactive strength assessment as it enables the measurement of an individual male hurling players' stretch load to maximize the drop-jump training effect. The identification of individualized DJ drop height from the BDJ test reduces the injury risk when employing DJs as a form of power training by individualizing the stretch load.

Future studies should examine the test-retest reliability of the highest RSI used to identify drop height for depth-jump training in other field sports from an incremental protocol of a number of heights. This type of investigation would be helpful in developing RSI profiles for field sports and would enable the comparison of field sports athletes at different levels of competition.

The current study has shown that drop height identified for BDJ is reliable when performing an incremental protocol using the highest RSI in male collegiate and club level hurling players. The highest RSI in this study has been shown to have an acceptable level of absolute and relative reliability based upon a variety of statistical tests. These findings are valuable for sport science practitioners, coaches and players seeking to use an incremental BDJ protocol in conjunction with the highest RSI. Employing the highest RSI assists in developing a reactive strength profile of the athlete for monitoring and/or identifying the drop height to be used for drop-jump training. The use of the highest RSI should enable players to maximize drop-jump training effects as well as reducing injury risk. The CMJ test has been shown to be reliable for a number of measures derived when using a force plate with hurling players. Measures such as force, power, velocity and rate of force development can provide indicators as to how forms of conditioning are impacting the player in terms of strength and power development. The reliability of absolute and relative ECC-RFD is valuable for sport science practitioners as they provide a means of understanding the mechanisms behind the adaptation to training.

Conclusion

To the best of our knowledge, the current study is the first to have estimated acceptable inter-day absolute and relative reliability for CMJ measures (except for peak concentric RFD measures) and BDJ measures in male hurling players that was conducted over three test sessions. The findings of the current study will add to the existing limited research available on hurling players and provide valuable data in terms of CMJ and BDJ measures for club and college level players. Furthermore, the findings may highlight the value of including RSI to monitor the effect of jump and sprint training due to its strong relationship with jumping and sprinting which are key athletic components required for hurling. The value of these findings in research terms means that sport science and strength and conditioning researchers involved in hurling have CMJ and BDJ measures that can determine feasible minimum sample sizes for an ANOVA RM.

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