

Research article

Influence of Sex and Maximum Strength on Reactive Strength Index-Modified

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Abstract

Reactive strength index-modified (RSImod) is a measure of lower body explosiveness calculated by dividing jump height by time to takeoff. RSImod is different between stronger and weaker athletes and between males and females. The purpose of this study was to evaluate differences in RSImod between males and females while controlling for maximal strength and lower body explosiveness. Forty-three female and fifty-eight male Division-I athletes performed countermovement jumps on a force plate during unloaded (0kg) and loaded (20kg) conditions. We used an ANCOVA to test whether RSImod is different between sexes conditioning on relative maximum strength (PFa) and average RFD 0-200ms (RFD200) measured during the isometric mid-thigh pull (IMTP). Differences of 0.087 (95% CI: 0.040 - 0.134; $p = 0.0005$) and 0.075 (95% CI: 0.040 - 0.109, $p < 0.0001$) were observed for RSImod between sexes in unloaded and loaded conditions, respectively. A male with PFa of 186 (grand mean of the sample) and RFD200 of 6602 N/s (grand mean of the sample) is predicted to have 28% greater RSImod than a female of similar PFa and RFD200. Maximum strength development should be a primary aim of training in female athletes, in addition to other trainable factors, such as stiffness and RFD.

Key words: Countermovement jump, sex difference, jump technique, isometric mid-thigh pull, reactive strength.

Introduction

While the height of a countermovement vertical jump (CMJ) is the result of the impulse generated by the jumper against the ground (Garhammer and Gregor, 1992; McBride et al., 2010), a variety of modifiable factors during the jump are ultimately related to how well he or she will jump. These factors include lower body power, reactive ability, and rate of force development (RFD) (Ham et al., 2007). One factor of particular importance to jump height and related characteristics is maximal strength (Ham et al., 2007; Suchomel et al., 2016). Maximal strength, the maximum force production ability of a muscle or a group of muscles (Komi, 2003), is a fundamental quality that underpins a variety of skills, not just the CMJ. Furthermore, this relationship between maximum strength and vertical jump appears to hold for both isometric and dynamic measures of lower body strength (Ham et al., 2007; Su-

chomel et al., 2016).

Previous literature has reported differing levels of lower body maximal strength between males and females, measured both absolutely and relatively (Jones et al., 2016). Additionally, differences in jumping ability (Castagna and Castellini, 2013; Sole et al., 2018a; Suchomel et al., 2015b), jumping kinematics/kinetics (Sole et al., 2018; Suchomel et al., 2015b), musculoskeletal stiffness characteristics (Granata et al., 2002a; Granata et al., 2002b; Kubo et al., 2003), and how effectively one uses the eccentric component of a jump (Castagna and Castellini, 2013; Sole et al., 2018a) have been observed between males and females. While maximal strength is generally related to vertical jump performance (Secomb et al., 2015), maximal strength scaled in some manner might better relate to this explosive skill, given that it requires an athlete to overcome her or his own inertia (i.e. the benefit of additional body mass to force production would be outweighed by the greater inertia overcome during the jump). Maximal strength is related to vertical jump height (Ham et al., 2007; Secomb et al., 2015; Suchomel et al., 2016), but this relationship is not perfect (i.e. $r < 1.0$), thus, it is plausible that relative maximal strength may explain much of the observed differences in the way that males and females jump (Sole et al., 2018a).

Reactive strength index-modified (RSImod) is a measure of lower body explosive strength that has shown promise as a tool for evaluating an athlete's performance (Kipp et al., 2016; Sole, Suchomel and Stone, 2018; Suchomel et al., 2015b). RSImod is calculated by dividing CMJ height by time to takeoff (TTT), accounting for how high an athlete is able to jump and how long it takes the athlete to apply force against the ground to do so. It has been shown to be both a reliable (Suchomel et al., 2015b) and valid measure of lower body explosive performance (Kipp et al., 2016; Suchomel et al., 2015b). RSImod sometimes varies between men's and women's collegiate DI teams (Sole 2018b; Suchomel et al., 2015b) and as a group, across multiple sports, men have greater RSImod than women (Sole et al., 2018b). In one study by Suchomel et al. (2015b), RSImod was different between men's and women's soccer teams at the same level of competition, but not between men's and women's tennis at the same level of competition. Measures of maximal strength were not

reported between teams in the previous study (Suchomel et al., 2015b), but in light of previous literature demonstrating strength differences between matched males and females, it seems a plausible explanation for why RSImod may or may not be different between males and females of similar sports and competitive level. In addition, because RSImod is purported to be a measure of lower body explosiveness, given known differences in RFD ability between males and females (Hannah et al., 2012), measures of RFD might also explain differences in RSImod between the sexes.

The aim of this study was to evaluate the difference in vertical jump performance between males and females while controlling for the effects of maximal strength measured during the isometric mid-thigh pull (IMTP). We hypothesized that maximal strength would be related to RSImod, but would not explain all of the difference between males and females. We also hypothesized that RSImod would be greater in males than in females.

Methods

Participants

Athletes in this study were 43 female and 58 male Division-I athletes (see Table 1 for descriptive statistics). Athletes played tennis (male $n = 5$, female $n = 11$), soccer (male $n = 24$, female $n = 20$), volleyball (female $n = 12$), and baseball (male $n = 29$). The performance tests used in this study were part of an ongoing athlete monitoring program, and the variables of interest were calculated from data obtained during this monitoring program. This retrospective study was approved by the University Institutional Review Board.

Table 1. Descriptive statistics. Data are mean \pm SD.

| | Females (n = 43) | Males (n = 58) |
|----------------|---------------------|-------------------|
| Body Mass (kg) | 67.0 \pm 9.7 | 82.7 \pm 10.5 |
| Height (m) | 1.69 \pm .07 | 1.80 \pm 0.07 |
| RSImod0 | 0.29 \pm 0.08 | 0.41 \pm 0.09 |
| JH0 (cm) | 25.5 \pm 6.3 | 35.1 \pm 6.4 |
| TTT0 (s) | 0.89 \pm 0.11 | 0.87 \pm 0.10 |
| RSImod20 | 0.18 \pm 0.06 | 0.291 \pm 0.07 |
| JH20 (cm) | 18.3 \pm 5.2 | 27.7 \pm 5.2 |
| TTT20 (s) | 1.04 \pm 0.16 | 0.97 \pm 0.12 |
| RFD200 (N/s) | 4285 \pm 2265 | 8338 \pm 2883 |
| PFa | 160.3 \pm 27.0 | 205.0 \pm 33.7 |

Design

Athletes that were part of an ongoing athlete monitoring program, performed maximal effort CMJs and the IMTP test in a single testing session. In a cross-sectional design, we wished to compare RSImod and its constituent variables under unloaded and loaded conditions between males and females, after controlling for the effects of strength and explosiveness on each of the dependent variables. We used analysis of covariance (ANCOVA), with maximum strength and explosiveness as covariates, to test for the sex differences.

Prior to the main data collection, athletes completed a standardised warm up. Athletes performed 25 jumping jacks, 1 set of 5 repetitions of mid-thigh pulls with 20 kg, then performed 3 sets of 5 repetitions with either 40 kg (fe-

males) or 60 kg (males). After warming up, athletes performed CMJs with a near-weightless (<1 kg) PVC pipe held across their shoulders. Each athlete started with two submaximal warm up jumps with 50% and 75% of their perceived maximum effort. After the warm up, they performed up to 4 CMJs until two acceptable trials were collected, separated by 30 seconds. Athletes were instructed to jump in a manner that would maximise their jump height. Trials were deemed acceptable when each were within 2 cm of each other and athletes felt they had performed a jump to the best of their ability.

Athletes performed all CMJs on a force plate (91 cm x 91 cm, Rice Lake, WI, USA) sampling at 1,000 Hz. Data were filtered using a digital low-pass 4th order Butterworth filter with a cutoff frequency of 10Hz. All data were collected and analyzed using a custom program in Labview 2010 (National Instruments Co., Austin Texas, USA). Jump height (JH) was calculated for the 0 kg (JH0) and 20 kg (JH20) conditions using flight time. TTT was determined as the length of time from the start of the unweighting phase of the CMJ until flight was achieved (beginning and end of each critical period determined using a 10N threshold). RSImod was calculated by dividing JH by TTT for both the 0 kg (RSImod0) and the 20 kg (RSImod20) conditions (Suchomel et al., 2015a; 2015b). Results from trial 1 and 2 were averaged for later analysis.

The procedures of the IMTP have been described previously (Beckham et al., 2018; Haff et al., 1997). Briefly, athletes entered a custom adjustable power rack that allows fixation of a horizontal bar at any height. The bar was adjusted to a height that allowed the athlete to assume a position that closely approximates the beginning of the second pull of the clean while standing on a dual force plate set up (2 plates, dimensions 45.5 cm x 91 cm; Rough-Deck HP; Rice Lake, WI, USA) underneath the rack. Athletes used an upright torso position, which results in a hip angle of approximately 145° (Beckham et al., 2018), and a goniometer-verified knee angle of 125 \pm 5° (Beckham et al., 2018). Athletes used lifting straps and were secured to the bar using athletic tape to eliminate grip as a limiting factor to performance.

Prior to the maximum effort pulls, and after the CMJs, athletes performed submaximal trials of the IMTP at their 50% and 75% perceived maximum effort. For the maximal effort pulls, the athlete was instructed to pull as "fast and hard as you can" to encourage high rates of force development and peak force (PF). Athletes stood in position to establish a stable baseline, then received a count-down, after which point the athlete exerted a maximal effort for 4 to 5 seconds. Strong verbal encouragement was provided to ensure maximal effort. Two IMTPs were performed by each athlete and the average of both trials was used for analysis. Athletes were allowed one minute of rest between each pull. PF obtained from the force-time trace (highest force observed value during the pull) was allometrically scaled to body mass (PFa) by dividing PF by body mass (BM) raised to the power of b (i.e. PFa = PF \cdot BM^b), where b is estimated from the data (Oba et al., 2014). Average RFD (RFD200) was calculated as the rate of change in force from the start of the pull (visually identified) to 200 ms.

Statistical analysis

To estimate the parameter b , instead of an initial assumption of the theoretical allometric exponent $b = 2/3$ (Jaric et al., 2005), a log-linear regression was used with sex and body mass (BM) adjustment (i.e., $\ln(\text{PFa}) = a + b \ln(\text{BM}) + c \text{sex}$, where $\text{sex} = 1$ for male and $\text{sex} = 0$ for female). The interaction of sex and BM was also tested within the scaling model to determine if separate models were justified by sex. Then PFa was defined as PF / BM^b , where b is estimated from the data.

Pearson product-moment correlations were used to assess the magnitude of vertical jump variables and IMTP variables.

Each vertical jump variable (RSImod0, JH0, and TTT0 for unloaded and RSImod20, JH20, and TTT20 for 20 kg loaded) was compared between sexes while controlling for the influence of strength (measured by PFa) and rapid force generation ability (measured by RFD200) using ANCOVA (i.e. $\text{RSImod0} = \beta_0 + \beta_1 \text{sex} + \beta_2 \text{PFa} + \beta_3 \text{RFD200}$, where $\text{sex} = 1$ for male and $\text{sex} = 0$ for female). Under the ANCOVA model, we addressed the research question through the parameter β_1 , which is interpreted as the difference in the average jump variable measurement when we compare males to females of the same PFa and RFD200.

For implementing the ANCOVA models, the Breusch-Pagan test was used for the constant variance assumption (Breusch & Pagan, 1979), and the likelihood ratio test was used for the constant slope assumption between males and females (Kutner et al., 2004). The normality assumption was not important in our data analysis as the sample size ($n = 101$) was sufficiently large to make valid inferences without the normality assumption. All statistical analyses were performed in R (version 3.3.2). Test-retest of each variable was evaluated using intraclass correlations (2,1) and typical error expressed as a coefficient of variation (Hopkins, 2011).

Results

The allometric exponent was estimated as $b = 0.695$, so PFa was calculated by $\text{PF} / \text{BM}^{0.695}$. There was no evidence to suggest the necessity of a sex-specific scaling exponent (i.e., the $\text{sex} \times \text{BM}$ interaction term in the scaling model was not statistically significant with $p = 0.300$). All tested variables were considered reliable ($\text{ICC} = 0.77\text{--}0.98$, typical error expressed as a $\text{CV} = 4.2\%\text{--}8.0\%$). RFD200 had a large CV (32%), but an acceptable ICC of 0.86. Descriptive statistics can be found in Table 1. For the unloaded condition, the mean RSImod0 for females was lower than for males by an average difference of 0.12, and the sample standard

deviations (SDs) were nearly same (0.29 ± 0.08 for females and 0.41 ± 0.09 for males). The mean JH0 for females was lower than for males by an average difference of 9.5 cm, and the observed jump height also showed nearly the same SD (25.5 ± 6.3 cm for females and 35.1 ± 6.4 cm for males). The mean TTT0 for females was higher than for males by an average of 0.03 seconds, and the sample SDs were nearly the same (0.89 ± 0.11 s for females and 0.87 ± 0.10 s for males). For the 20 kg loaded condition, the mean RSImod20 for females was lower than for males by an average difference of 0.11 with similar SDs (0.18 ± 0.06 for females and 0.291 ± 0.07 for males). The mean JH20 for females was lower than for males by an average difference of 9.3 cm, with similar SDs (18.3 ± 5.2 for females and 27.7 ± 5.2 for males). The mean TTT20 for females was higher than for males by an average of 0.07 seconds, and the sample SD for females was about 32% greater than the SD for males (1.04 ± 0.16 s $\text{CV} = 15.4\%$ for females and 0.97 ± 0.12 s, $\text{CV} = 12.4\%$ for males).

As shown in Table 2, based on the Pearson correlations denoted by r , RSImod0, RSImod20, JH0, and JH20 were significantly correlated with PFa ($r = 0.50\text{--}0.61$) and with RFD200 ($r = 0.36\text{--}0.55$), but TTT0 and TTT20 were not (or very weakly) correlated with PFa and RFD200.

Table 3 has results for the ANCOVA test comparing males and females for the six jump variables conditioning on PFa and RFD200. The sex difference was statistically significant with RSImod and JH for both unloaded and loaded conditions, with TTT20 but not with TTT0. On average, males had 0.0868 greater RSImod in the unloaded condition, and 0.0747 greater RSImod in the loaded condition. The estimated average difference in jump height, male minus female, was 6.04 cm for the unloaded condition (JH0) and 5.70 cm for the loaded condition (JH20). Under the unloaded condition, males and females showed a non-significant difference of 0.0398 s in the average time to takeoff (TTT0), but females were 0.079 s slower than males in the estimated average of TTT20 (i.e., 20 kg load). Given PFa and sex, RFD200 was no longer a statistically significant covariate for RSImod and JH (both unloaded and loaded). Figure 1 shows that both RSImod and jump height tend to be higher as PFa is higher, and when we control for PFa and RFD200, males jump higher than females on average. In Figure 2, the average time to takeoff is similar under the unloaded condition, but females' average is greater than males' average under the 20 kg loaded condition. In addition, it should be noted that under the 20 kg loaded condition, females show more variability (i.e., more dispersed distribution) in the time to takeoff compared to when they are unloaded.

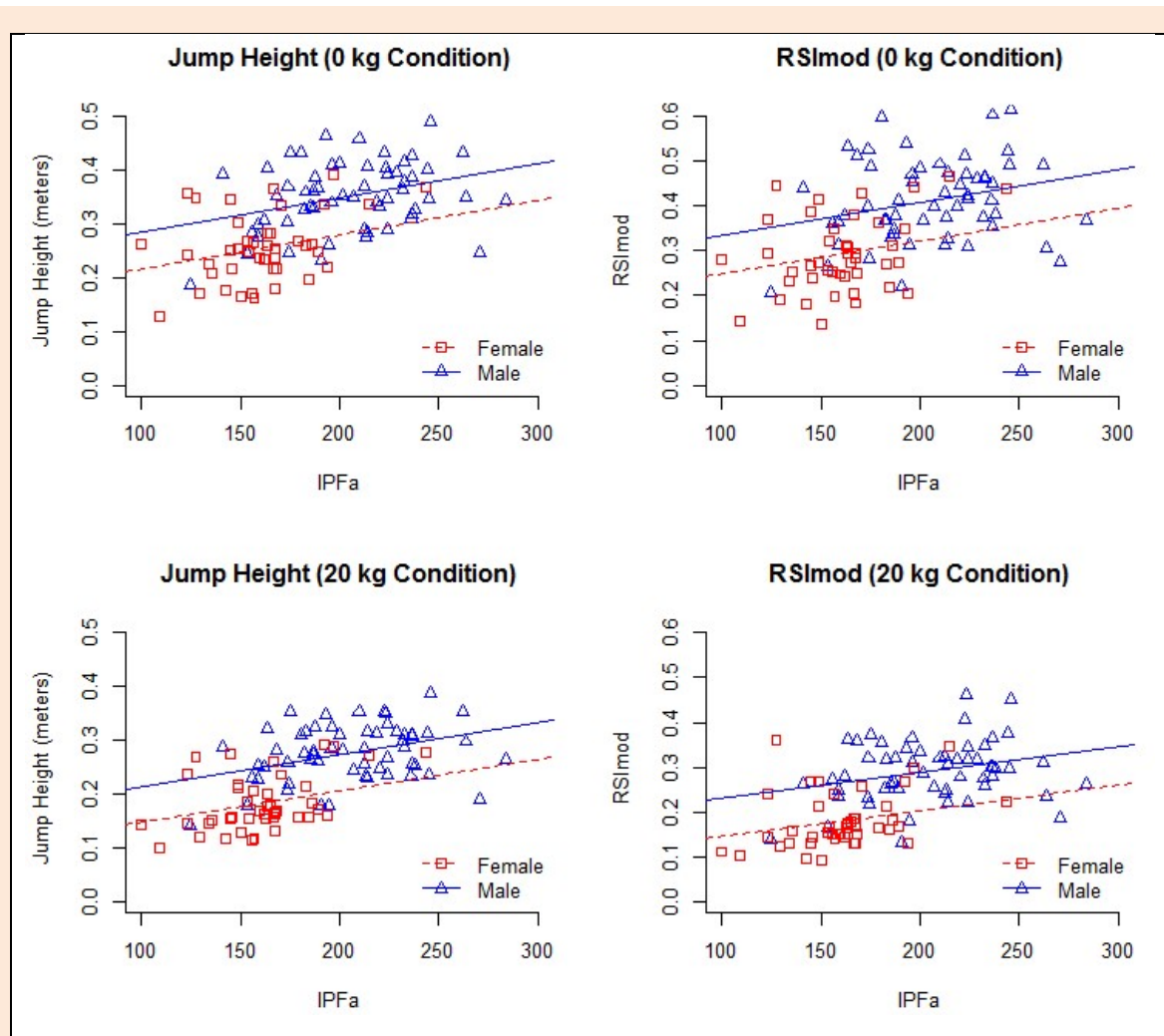
Table 2. Relationship of vertical jump variables to allometrically scaled peak force (PFa).

| | Correlation with PFa (p-value) | Correlation with RFD200 (p-value) |
|------------------------|--------------------------------|-----------------------------------|
| RSImod (0kg) | 0.50 (< 0.0001)* | 0.36 (0.0003)* |
| RSImod (20kg) | 0.55 (< 0.0001)* | 0.49 (< 0.0001)* |
| Jump Height (0kg) | 0.55 (< 0.0001)* | 0.45 (< 0.0001)* |
| Jump Height (20kg) | 0.61 (< 0.0001)* | 0.55 (< 0.0001)* |
| Time to Takeoff (0kg) | -0.07 (0.5101) | 0.02 (0.8121) |
| Time to Takeoff (20kg) | -0.14 (0.1704) | -0.08 (0.4369) |

* indicates statistical significance at $p \leq 0.05$

Table 3. Estimated parameter and standard error under the ANCOVA model.

| Response | Variables | Estimate | SE | 95% CI | P-value |
|----------|-------------------------|-----------------------|--------------------|--|----------|
| RSImod0 | Intercept (β_0) | 0.1864 | 0.0484 | (0.0914, 0.2813) | 0.0002 |
| | Sex (β_1) | 0.0868 | 0.024 | (0.0399, 0.1338) | 0.0005 |
| | PFa (β_2) | 0.0007 | 0.0003 | (0.0001, 0.0013) | 0.0206 |
| | RFD200 (β_3) | -1×10^{-6} | 4×10^{-6} | (-8×10^{-6} , 6×10^{-6}) | 0.7517 |
| SImod20 | Intercept (β_0) | 0.1002 | 0.0353 | (0.0309, 0.1694) | 0.0056 |
| | Sex (β_1) | 0.0747 | 0.0175 | (0.0404, 0.1089) | < 0.0001 |
| | PFa (β_2) | 0.0005 | 0.0002 | (0.0000, 0.0009) | 0.0396 |
| | RFD200 (β_3) | 2×10^{-6} | 3×10^{-6} | (-3×10^{-6} , 8×10^{-6}) | 0.3502 |
| JH0 | Intercept (β_0) | 0.1641 | 0.0343 | (0.0969, 0.2312) | < 0.0001 |
| | Sex (β_1) | 0.0604 | 0.0169 | (0.0272, 0.0936) | 0.0006 |
| | PFa (β_2) | 0.0006 | 0.0002 | (0.0001, 0.0010) | 0.0122 |
| | RFD200 (β_3) | 2×10^{-6} | 3×10^{-6} | (-3×10^{-6} , 7×10^{-6}) | 0.5374 |
| JH20 | Intercept (β_0) | 0.0983 | 0.0272 | (0.0450, 0.1516) | 0.0005 |
| | Sex (β_1) | 0.0570 | 0.0134 | (0.0307, 0.0834) | 0.0001 |
| | PFa (β_2) | 0.0005 | 0.0002 | (0.0001, 0.0008) | 0.0078 |
| | RFD200 (β_3) | 3×10^{-6} | 2×10^{-6} | (-1×10^{-6} , 7×10^{-6}) | 0.1271 |
| RSImod0 | Intercept (β_0) | 0.8868 | 0.0591 | (0.7710, 1.0026) | < 0.0001 |
| | Sex (β_1) | -0.0398 | 0.0292 | (-0.0970, 0.0174) | 0.1763 |
| | PFa (β_2) | -0.0001 | 0.0004 | (-0.0008, 0.0006) | 0.7777 |
| | RFD200 (β_3) | 5×10^{-6} | 4×10^{-6} | (-4×10^{-6} , 1.4×10^{-5}) | 0.2540 |
| TTT20 | Intercept (β_0) | 1.0198 | 0.0776 | (0.8676, 1.1719) | < 0.0001 |
| | Sex (β_1) | -0.0791 | 0.0384 | (-0.1544, -0.0039) | 0.0421 |
| | PFa (β_2) | -1.3×10^{-5} | 0.0005 | (-0.0010, 0.0009) | 0.9792 |
| | RFD200 (β_3) | 4×10^{-6} | 6×10^{-6} | (-8×10^{-6} , 1.5×10^{-5}) | 0.5139 |

**Figure 1.** The relationship of PFa to JH0 and JH20, and PFa to RSImod0 and RSImod20 for male and female athletes performing the countermovement jump. (The non-significant covariate RFD200 was not considered in this figure.)

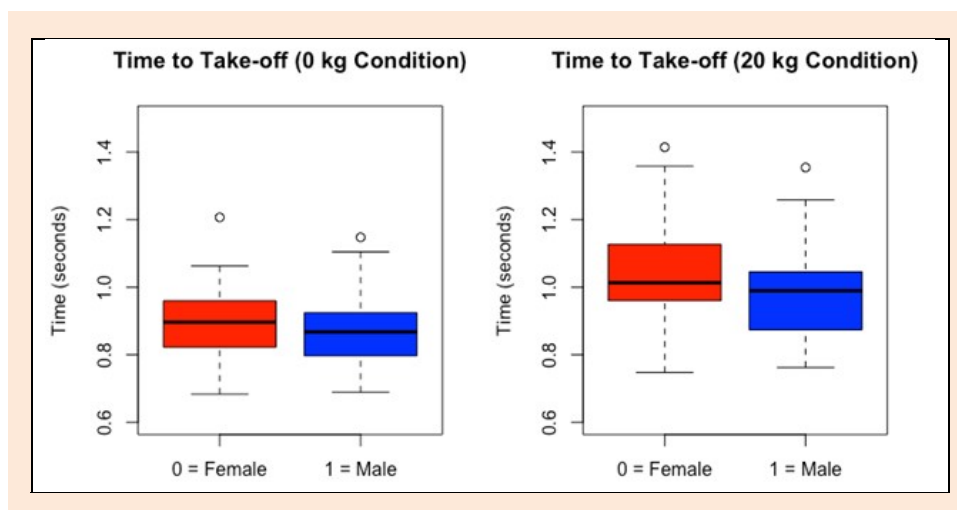


Figure 2. Boxplots for time to takeoff for male and female athletes performing the loaded and unloaded countermovement jump. In both cases, females took slightly longer to leave the ground. The time to takeoff was more varied for both sexes when jumping with a 20kg weight.

For all ANCOVA models implemented in the analyses, the Breusch-Pagan test and the likelihood ratio test could not detect any violation of the constant variance assumption and the constant slope assumption.

Discussion

Reactive strength index-modified, calculated for both loaded and unloaded jumps, is related to lower-body allometrically-scaled maximal strength expressed in the IMTP test. Previous research has suggested that strength is a limiting factor in jumping ability and other lower body measures of explosive strength characteristics (Suchomel et al., 2016). A previous study also found that the reactive strength index, calculated similarly to RSImod but during depth jumps, was also related to allometrically scaled PF measured during the IMTP (Beattie et al., 2017). Interestingly, when the strongest and weakest jumpers in the previous study were stratified, there were moderate to large differences in JH, ground contact time, and reactive strength index, with differences between the strong and weak groups growing with greater drop heights (Beattie et al., 2017). Stratifying between stronger and weaker athletes has shown differences in CMJ height, RSImod, and TTT in other studies (Dos'Santos et al., 2017). Given the relationship between jumping and lower body strength, it was justified to control for maximal strength when attempting to elucidate differences in how men and women jump. Past research has demonstrated that there are differences in strength (Jones et al., 2016) and JH (Castagna and Castellini, 2013; Suchomel et al., 2015b) between males and females, although less is understood about differences that might exist in jumping strategies between males and females. Findings from the current study indicate that maximal strength is related to RSImod and JH, but after statistically controlling for relative maximal strength, there is still a difference between men and women for RSImod for loaded and unloaded CMJs. This indicates that there must be other factors that explain observed differences in RSImod

between males and females than simply lower body strength.

Both RSImod and JH, measured when unloaded and loaded, were different between sexes in the present study after controlling for strength. Interestingly, TTT in an unloaded condition was not different between males and females. This would appear to indicate that it is JH and not TTT that contributes most to the greater RSImod observed in males. Mechanically, this means that on average, male athletes generate greater impulse in a similar amount of time as their female counterparts. A study by McMahon et al. (2017) found that eccentric and concentric impulse, scaled to body mass, was statistically greater in male athletes, supporting this explanation. This greater impulse could be the result of greater RFD or greater peak forces, or both, during various phases of the CMJ (Sole et al., 2018a). In contrast, TTT20 was different between males and females. Greater decrements in CMJ performance under unloaded conditions have been previously explained by lower strength (Kraska et al., 2009), but strength was controlled for in this study, eliminating it as a possible explanation for the increased TTT20 in the loaded condition. One possible reason for the greater TTT20 in females could be the fact that the 20kg bar represents a greater proportional load relative to their body weight. This explanation needs further examination in future research.

The CMJ starts with the countermovement-unweighting phase, in which the athlete rapidly drops down from his or her starting position, then quickly applies force eccentrically to slow their descent and change direction, called the countermovement stretching/braking phase (McMahon et al., 2018). Once sufficient impulse has been generated to change direction, the propulsion phase begins, in which forces are generated concentrically to propel the athlete into the air (McMahon et al., 2018). The forces/impulse generated during each of these phases dictates the change in momentum the athlete experiences and thus the takeoff velocity of the athlete as they leave the ground, and the maximum jump height the athlete will reach. The im-

pulse-momentum relationship dictates that the amount of impulse applied to an object is responsible for the proportional change in momentum the object experiences. Consequently, for vertical jumps, maximization of impulse will result in the maximization of takeoff velocity, leading to a greater jump height. Unfortunately, little is understood about how force generation might differ between each sex, especially with regard to force production in each phase of the jump.

The greater impulse that results in larger jump heights in males could be applied in any or all of the phases of the CMJ. One recent study found that during the CMJ, males exhibited greater peak forces in the stretching, net impulse, and propulsion-acceleration I phases, and higher relative impulses in the net impulse and propulsion-acceleration I phases (Sole et al., 2018a). Interestingly, phase durations of the CMJ were similar between men and women, leading the authors to suggest that it is non-temporal factors that are primarily responsible for better CMJ performance, agreeing with the findings of the present study and others (Laffaye et al., 2014). On the other hand, McMahon et al. (2017) found that there was a small, albeit non-statistically significant difference (Hedges' g of 0.53) in time to takeoff between males and females, although this could potentially be explained by the fact that each sex group came from different sports.

Increased impulse within the countermovement stretching phase may partially explain the difference in JH and RSImod between sexes, due to known differences in lower-body stiffness (Granata et al., 2002b; Wang et al., 2015), increased tendon stiffness (Kubo et al., 2003), and greater vertical stiffness measured in hopping tasks (Granata et al., 2002a) in men. The increased stiffness observed in males may lead to a more effective ability to exert high rates of force development, due to lower electromechanical delay (Grosset et al., 2009) and enhanced force transmission. On a molecular basis, titin plays an important role in the forces and stiffness exhibited during eccentric tasks (Herzog, 2014), thus it is possible that the characteristics of titin may display some sex differences, although this has not yet been tested to the authors' knowledge.

Musculotendinous stiffness is associated with rate of torque development (Bojsen-Møller et al., 2005), maximal CMJ height (Bojsen-Møller et al., 2005), and other countermovement kinetic/kinematic measures (Bojsen-Møller et al., 2005). Vertical stiffness, measured during jumping tasks, is related to CMJ height (Secomb et al., 2015) and to reactive strength index measured in drop jumps (Kipp et al., 2018). This increased stiffness, among other factors, could potentially explain differences in CMJ performance between sexes. Isometric PF, measured during the IMTP has also been shown to be related to vertical stiffness (Secomb et al., 2015). It is possible that the influence of underlying mechanisms for both PFa and vertical stiffness were removed by the ANCOVA procedure in the present study, removing some of the possible benefit held by the increased stiffness observed in male athletes. Still, notable differences remained in the dependent variables of this study after controlling for relative maximum strength (a difference of 0.0865 for RSImod0, 6.64 cm for JH0, 0.0832 for RSImod20, and 6.66 cm for JH20).

Interestingly, Kubo et al. (2003) observed that females had lower hysteresis of tendon and aponeurosis of the medial gastrocnemius than males, indicating that females may have a more effective storage of elastic energy during the stretch-shortening cycle. Combined with the finding that female national team soccer players have a greater difference in JH between a CMJ and a static jump (no countermovement, thus no stretch-shortening cycle) versus male national team soccer players, it appears that females may more effectively store and use elastic energy (Castagna and Castellini, 2013). However, this explanation may or may not apply to the CMJ: a recent review suggested that the stretch-shortening cycle may not play as big a role in CMJ performance as previously believed (Van Hooren and Zolotarjova, 2017). Should the stretch-shortening cycle make only a small contribution to CMJ performance, then an increased ability to store elastic energy by female athletes may have little additional benefit to their ability to perform a countermovement.

One potentially confounding factor in the comparison of RSImod between male and female athletes is the fact that athletes came from a variety of different teams. Differences in RSImod observed between teams are potentially related to both the demands of their sport and the differences in how they are trained (Sole et al., 2018b). Sports with an emphasis on vertical motions, such as volleyball, may have different relationships with RSImod than sports with an emphasis on more horizontal motions, such as soccer. Further research should examine the influence of sport on sex differences, and future research should make sex comparisons across athletes of similar sport backgrounds.

Exponents used to scale IMTP PF results were calculated from this study's sample, rather than using a scaling exponent from prior studies. The estimated allometric exponent $b = 0.695$ was used for PFa in this study, but we could not find statistical evidence that b is different than the $2/3$ exponent commonly used in other IMTP studies. An estimated 95% CI was (0.443, 0.947), which overlaps the $2/3$ exponent commonly used in other research. The $2/3$ exponent, while initially validated against the weightlifting totals of male weightlifters (Lietzke, 1956), appears also to be valid for PF results from the IMTP. Given that the body position used for the IMTP is based upon a key position of the clean (Haff et al., 1997), use of the $2/3$ exponent has face validity, and validity for our sample. Additionally, when an interaction model $\ln(\text{PF}) = a + b \ln(\text{BM}) + c \text{sex} + d \ln(\text{BM}) \times \text{sex}$ was considered for development of the exponent in our study, we had a lack of evidence for sex-specific allometric exponents. To this end, the data (at least for this study population) were not against the assumption of $b = 2/3$ for both sexes. Whether we used the estimate $b = 0.695$ or the theoretical value $b = 2/3$, the conclusions from the ANCOVA model remain the same.

Conclusion

While maximum strength explains a meaningful amount of difference in RSImod and jump height between males and females, after controlling for maximum strength, there are still differences in jump characteristics between males and females. This difference might come as a result of muscu-

lotendinous stiffness, vertical stiffness, or some as-yet undiscovered difference between sexes. Further research is necessary to continue to elucidate these differences. Maximum strength and RFD200 does not however explain the entirety of differences in JH or RSImod in unloaded and loaded conditions between males and females. Coaches should address other trainable qualities in addition to maximal strength such as RFD and leg stiffness, particularly so in females.

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References

- Beattie, K., Carson, B. P., Lyons, M. and Kenny, I. C. (2017) The Relationship Between Maximal Strength and Reactive Strength. *International Journal of Sports Physiology and Performance* **12**, 548-553.
- Beckham, G. K., Sato, K., Santana, H. A. P., Mizuguchi, S., Haff, G. G. and Stone, M. H. (2018) Effect of Body Position on Force Production During the Isometric Midthigh Pull. *Journal of Strength and Conditioning Research* **32**, 48-56.
- Bojsen-Møller, J., Magnusson, S. P., Rasmussen, L. R., Kjaer, M. and Aagaard, P. (2005) Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. *Journal of Applied Physiology* **99**, 986-994.
- Breusch, T. S. and Pagan, A. R. (1979) A simple test for heteroscedasticity and random coefficient variation. *Econometrica* **47**, 1287-1294.
- Castagna, C. and Castellini, E. (2013) Vertical jump performance in Italian male and female national team soccer players. *Journal of Strength and Conditioning Research* **27**, 1156-1161.
- Dos Santos, T., Thomas, C., Comfort, P., McMahon, J. J. and Jones, P. A. (2017) Relationships between Isometric Force-Time Characteristics and Dynamic Performance. *Sports* **5**, 68.
- Garhammer, J. and Gregor, R. (1992) Propulsion forces as a function of intensity for weightlifting and vertical jumping. *Journal of Strength and Conditioning Research* **6**, 129-134.
- Granata, K. P., Padua, D. A. and Wilson, S. E. (2002a) Gender differences in active musculoskeletal stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. *Journal of Electromyography and Kinesiology* **12**, 127-135.
- Granata, K. P., Wilson, S. E. and Padua, D. A. (2002b) Gender differences in active musculoskeletal stiffness. Part I. Quantification in controlled measurements of knee joint dynamics. *Journal of Electromyography and Kinesiology* **12**, 119-126.
- Grosset, J.-F., Piscione, J., Lambert, D. and Pérot, C. (2009) Paired changes in electromechanical delay and musculo-tendinous stiffness after endurance or plyometric training. *European Journal of Applied Physiology* **105**, 131-139.
- Haff, G. G., Stone, M., O'Bryant, H. S., Harman, E., Dinan, C., Johnson, R. and Han, K.-H. (1997) Force-Time Dependent Characteristics of Dynamic and Isometric Muscle Actions. *Journal of Strength and Conditioning Research* **11**, 269-272.
- Ham, D. J., Knez, W. L. and Young, W. B. (2007) A deterministic model of the vertical jump: implications for training. *Journal of Strength and Conditioning Research* **21**, 967-972.
- Hannah, R., Minshull, C., Buckthorpe, M. W. and Folland, J. P. (2012) Explosive neuromuscular performance of males versus females. *Experimental Physiology* **97**, 618-629.
- Herzog, W. (2014) Mechanisms of enhanced force production in lengthening (eccentric) muscle contractions. *Journal of Applied Physiology* **116**, 1407-1417.
- Hopkins, W. G. (2011) Precision of Measurement. *A New View of Statistics*. Retrieved from <http://www.sportsci.org/resource/stats/precision.html>
- Jaric, S., Mirkov, D. and Markovic, G. (2005) Normalizing physical performance tests for body size: a proposal for standardization. *Journal of Strength and Conditioning Research* **19**, 467-474.
- Jones, M., Jagim, A., Haff, G., Carr, P., Martin, J. and Oliver, J. (2016) Greater Strength Drives Difference in Power between Sexes in the Conventional Deadlift Exercise. *Sports* **4**, 43.
- Kipp, K., Kiely, M. T. and Geiser, C. F. (2016) Reactive Strength Index Modified Is a Valid Measure of Explosiveness in Collegiate Female Volleyball Players. *Journal of Strength and Conditioning Research* **30**, 1341-1347.
- Kipp, K., Kiely, M. T., Giordaneli, M. D., Malloy, P. J. and Geiser, C. F. (2018) Biomechanical Determinants of the Reactive Strength Index During Drop Jumps. *International Journal of Sports Physiology and Performance* **13**, 44-49.
- Kraska, J. M., Ramsey, M. W., Haff, G. G., Fethke, N., Sands, W. A., Stone, M. E. and Stone, M. H. (2009) Relationship between strength characteristics and unweighted and weighted vertical jump height. *International Journal of Sports Physiology and Performance* **4**, 461-473.
- Komi, P. (2003) *Strength and Power in Sport*. 2nd Edition (Vol. 3). Blackwell Science Ltd.
- Kubo, K., Kanehisa, H. and Fukunaga, T. (2003) Gender differences in the viscoelastic properties of tendon structures. *European Journal of Applied Physiology* **88**, 520-526.
- Kutner, M., Nachtsheim, C., Neter, J., & Li, W. (2004) *Applied Linear Statistical Models*. 5th Edition. New York, NY: McGraw-Hill/Irwin.
- Laffaye, G., Wagner, P. P. and Tombleson, T. I. L. (2014) Countermovement jump height: gender and sport-specific differences in the force-time variables. *Journal of Strength and Conditioning Research* **28**, 1096-1105.
- Lietzke, M. H. (1956) Relation Between Weightlifting Totals and Body Weight. *Science* **124**, 486-487.
- McBride, J. M., Kirby, T. J., Haines, T. L. and Skinner, J. (2010) Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads. *International Journal of Sports Physiology and Performance* **5**, 484-496.
- McMahon, J. J., Rej, S. J. E. and Comfort, P. (2017) Sex Differences in Countermovement Jump Phase Characteristics. *Sports* **5**, 8.
- McMahon, J. J., Suchomel, T. J., Lake, J. P. and Comfort, P. (2018) Relationship Between Reactive Strength Index Variants in Rugby League Players. *Journal of Strength and Conditioning Research* Epub print Feb 1.
- Oba, Y., Hetzler, R. K., Stickley, C. D., Tamura, K., Kimura, I. F. and Heffernan, T. P., Jr (2014) Allometric Scaling of Strength Scores in NCAA Division I-A Football Athletes. *Journal of Strength and Conditioning Research* **28**, 3330-3337.
- Secomb, J. L., Lundgren, L. E., Farley, O. R., Tran, T. T., Nimphius, S., and Sheppard, J. M. (2015) Relationships Between Lower-Body Muscle Structure and Lower-Body Strength, Power, and Muscle-Tendon Complex Stiffness. *Journal of Strength and Conditioning Research* **29**, 2221-2228.
- Sole, C. J., Mizuguchi, S., Sato, K., Moir, G. L. and Stone, M. H. (2018a) Phase Characteristics of the Countermovement Jump Force-Time Curve: A Comparison of Athletes by Jumping Ability. *Journal of Strength and Conditioning Research*, **32**, 1155-1165.
- Sole, C. J., Suchomel, T. J. and Stone, M. H. (2018b) Preliminary Scale of Reference Values for Evaluating Reactive Strength Index-Modified in Male and Female NCAA Division-I athletes. *Sports* **6**, 133.
- Suchomel, T. J., Bailey, C. A., Sole, C. J., Grazer, J. L. and Beckham, G. K. (2015a) Using reactive strength index-modified as an explosive performance measurement tool in Division I athletes. *Journal of Strength and Conditioning Research* **29**, 899-904.
- Suchomel, T. J., Nimphius, S. and Stone, M. H. (2016) The Importance of Muscular Strength in Athletic Performance. *Sports Medicine* **46**, 1419-1449.
- Suchomel, T. J., Sole, C. J., Bailey, C. A., Grazer, J. L. and Beckham, G. K. (2015b) A comparison of reactive strength index-modified between six U.S. Collegiate athletic teams. *Journal of Strength and Conditioning Research* **29**, 1310-1316.
- Van Hooren, B. and Zolotarjova, J. (2017) The Difference Between Countermovement and Squat Jump Performances: A Review of Underlying Mechanisms With Practical Applications. *Journal of Strength and Conditioning Research* **31**, 2011-2020.
- Wang, D., Vito, G. D., Ditroilo, M., Fong, D. T. P. and Delahunt, E. (2015) A comparison of muscle stiffness and musculoarticular

stiffness of the knee joint in young athletic males and females.
Journal of Electromyography and Kinesiology **25**, 495-500.

Key points

- Despite controlling for the effects of maximum strength and explosiveness, differences in RSImod and its constituent parts exist between males and females.
- The differences observed between males and females don't seem to increase with additional load, with the exception of time to takeoff, which may be a function of use of a greater portion of females' body mass.
- Use of a 2/3 exponent in the allometric scaling equation for isometric mid-thigh pull PF results appears valid, at least for a sample of young adult athletes.

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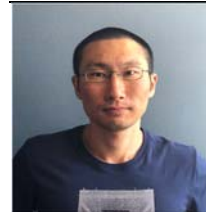
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