COUNTERMOVEMENT JUMP HEIGHT: GENDER AND SPORT-SPECIFIC DIFFERENCES IN THE FORCE-TIME VARIABLES

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ABSTRACT

Laffaye, G, Wagner, PP, and Tombleson, TIL. Countermovement jump height: Gender and sport-specific differences in the force-time variables. *J Strength Cond Res* 28(4): 1096–1105, 2014–The goal of this study was to assess (a) the eccentric rate of force development, the concentric force, and selected time variables on vertical performance during countermovement jump, (b) the existence of gender differences in these variables, and (c) the sport-specific differences. The sample was composed of 189 males and 84 females, all elite athletes involved in college and professional sports (primarily football, basketball, baseball, and volleyball). The subjects performed a series of 6 countermovement jumps on a force plate (500 Hz). Average eccentric rate of force development (ECC-RFD), total time (TIME), eccentric time (ECC-T), Ratio between eccentric and total time (ECC-T:T) and average force (CON-F) were extracted from force-time curves and the vertical jumping performance, measured by impulse momentum. Results show that CON-F ($r = 0.57$; $p < 0.001$) and ECC-RFD ($r = 0.52$, $p < 0.001$) are strongly correlated with the jump height (JH), whereas the time variables are slightly and negatively correlated ($r = -0.21–0.23$, $p < 0.01$). Force variables differ between both sexes ($p < 0.01$), whereas time variables did not differ, showing a similar temporal structure. The best way to jump high is to increase CON-F and ECC-RFD thus minimizing the ECC-T. Principal component analysis (PCA) accounted for 76.8% of the JH variance and revealed that JH is predicted by a temporal and a force component. Furthermore, the PCA comparison made among athletes revealed sport-specific signatures: volleyball players revealed a temporal-prevailing profile, a weak-force with large ECC-T:T for basketball players and explosive and powerful profiles for football and baseball players.

KEY WORDS strength, concentric, athletic

INTRODUCTION

Critical information can be directly extracted from the force-time (F-T) curve during the vertical countermovement jump (CMJ), such as time variables, force variables, and variables linking both components (rate of force development, impulse, and power). This information allows trainers and scientists to understand how a subject jumps, specifically the different phases of the movement (eccentric vs. concentric). Moreover, several studies have shown that the shape of the F-T curve is dependent on expertise (9,11,12). This means that with training, neuromuscular properties of the athlete change (10) by increasing the level of force with a higher preload during the eccentric phase, by allowing high interaction between contractile and elastic elements, and by storing and using elastic energy and activating the stretch reflex (6,8,11,16). Considering that the performance during CMJ is the result of the high level of efficiency of all these mechanisms, it is expected that the vertical performance is strongly linked to the mechanical variables responsible for the force production in the concentric and eccentric phases, and in turn, the contribution of the elastic elements and nervous system properties.

More specifically, rate of force development (RFD) seems to play a crucial role in activities involving plyometric muscular contractions, such as sprinting or jumping (15,20,26,34,36,37,46). Rate of force development could be defined as the rate of rise of contractile force at the beginning of muscle action (39). Rate of force development has been frequently studied as a force-time variable (1,5,15,20,26,34,36,37,46) often during the concentric phase when the peak occurs, but very rarely during the eccentric phase (11,24) and even less so when taken as an average. This variable has been demonstrated as a crucial variable (6,8,11,16) in the ability to enhance the stretch-shortening cycle (SSC).

Analysis of force-time curves reveal gender-specific differences in jump heights (JHs). Various studies show that men tend to jump higher than women (approximately 10 cm) throughout a range of different jump methods (CMJ and Drop Jump) (2,23,33,44,45). This is primarily explained by higher value of relative power, force (2,18,33), and the difference in the eccentric time (29). But only 3 studies have investigated the gender difference in RFD (5,15,25) and only

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1 during a plyometric activity, i.e., the CMJ (15). The latter study did not find any RFD difference between men and women, meaning curiously no difference in the efficiency of the prestretching phase of jump.

Finally, few studies have investigated sport-specific differences with regard to force-time variables (28,32). These studies demonstrate the role of sport and practice in shaping jumping components. Athletes seem to use jumping strategies, which reveal the specific constraints of their sport. An explosive and force-prevailing profile has been noticed for high jumpers, a time-prevailing profile for volleyball players (32) and a heterogeneous and neutral component for handball and basketball players (28,32). For the best of our knowledge, the force-time signature of football and baseball players has never been investigated.

Therefore, based on this theoretical background, the goal of the present study is to (a) assess the contribution of ECC-RFD, the CON-F, and the selected time variables on the vertical performance during CMJ, (b) assess the gender differences in these variables, (c) explain the link between these variables, and (d) investigate whether sport-specific "signatures" or profiles exist with regard to the inherent demands of their sport.

METHODS

Experimental Approach to the Problem

The subjects arrived for testing in groups of 2–5 people at a time, on commencement of their training term at the facility. The testing sessions were initiated with a thorough description of the testing procedure before the actual assessment. This was immediately followed by a standardized 10-minute warm-up consisting of self-myofacial release and a number of total body dynamic stretches. After the warm-up, subjects were then adequately familiarized with the jump testing with 2 submaximal practice jumps before testing. The testing procedure itself consisted of each subject performing a series of 6 jumps with 30 seconds rest in-between. The subjects were instructed to jump as high as they could by performing a CMJ with an arm swing. No instruction was given on the technique to be used during the CMJ, considering the fact that in skilled jumpers, subjects chose the depth that maximized both peak force and peak velocity resulting in maximal power output (27). Analysis of variance (ANOVA) and correlation coefficients were used to analyze the force-time variables from the force plate. Average eccentric rate of force development (ECC-RFD), total time (TIME), eccentric time (ECC-T), ratio between eccentric time and total time (ECC-T:T), and average vertical concentric force (CON-F) were extracted from the force-time curve and the vertical performance. Vertical JH was calculated from impulse momentum (19,35).

Subjects

A total of 273 subjects, including 189 males and 84 females, were used in the study with all major physical characteristics summarized in Table 1. All of the participants were of an elite standard, competing at a college or professional level in a range of sports, including volleyball, basketball, baseball, football, or others. Due to the samples sporting level, all subjects were experienced strength and power athletes, performing training of this nature at least 2 times per week as a part of their typical training regime.

Each volunteer signed a written informed consent statement before the investigation after receiving oral and written description of the procedures in accordance with guidelines established by the University Human Subject Review Board. They were informed of the risks and benefits of participation in this study. Moreover, the procedure of this study was approved by the research ethics committee of the University Paris-Sud.

Procedures

Vertical Jump. All testing was performed with the subject standing on a 0.6 × 0.4-m Bertec 4060-08 piezoelectric force sensor platform (Bertec Corporation, Columbus, OH) with a sampling frequency of 500 Hz. A 20-minute warm-up was performed that consists of standardized 30-second blocks within 10 minutes of myofascial release and 10 minutes of muscle activation and stretching and a familiarization session of CMJ. Then, each subject started the CMJ in the standing position, dropped into the squat position, and then immediately jumped as high as possible. The depth of knee flexion and the amount of arm movement used during each CMJ was individually determined by each subject, considering the fact that in skilled jumpers, subjects chose the depth that

TABLE 1. Anthropometrics and general statistics of subjects by sport categories: mean (*SD*).*

		Age (y)		Height (m)		Body mass (kg)	
	N	Males	Females	Males	Females	Males	Females
Basketball	50	27 (3.2)	23	2.04 (0.24)	1.86 (0.21)	73.2 (14.5)	61.9 (7.1)
Football	40	31 (2.6)	9	1.83 (0.22)	1.71 (5.5)	89.5 (17.2)	57.7 (7.7)
Volleyball	55	27 (2.8)	28	1.98 (0.1)	1.86 (0.19)	77.2 (5.9)	69.5 (10.4)
Baseball	84	24 (3.1)	NA	1.83 (0.09)	NA	86.8 (11.8)	NA
Others	44	28 (4.2)	16	1.81 (0.12)	1.68 (0.3)	75.6 (6)	59 (3.3)

*NA, not available.

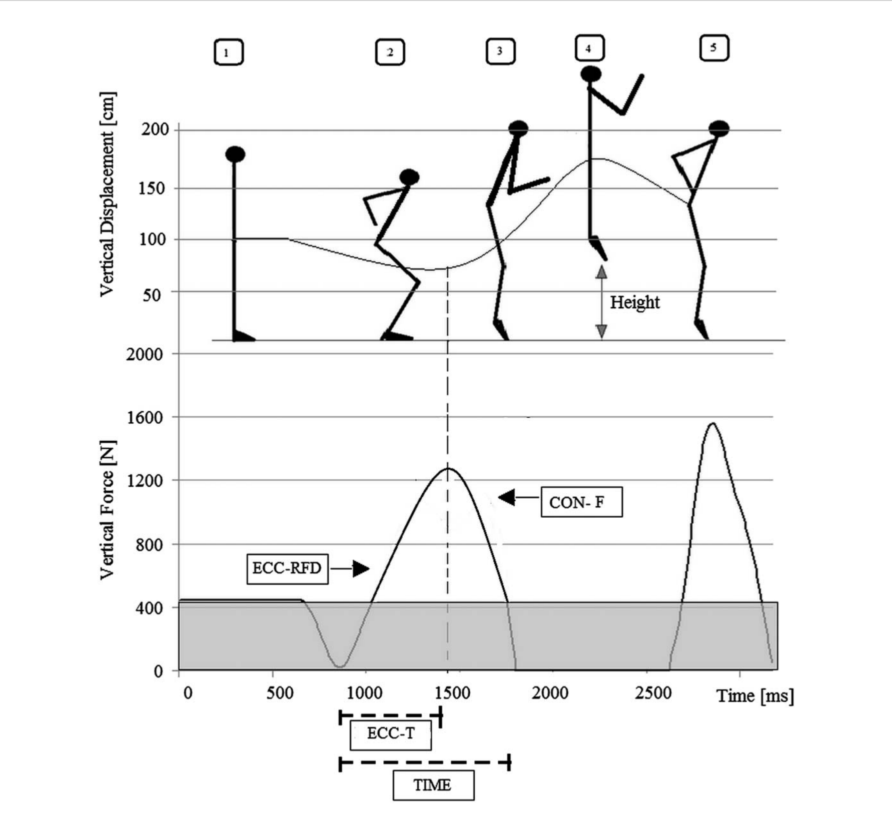

Figure 1. A typical countermovement jump: the upper curve represents the center of mass displacement (in centimeters), the lower curve shows the force (Fz) and their corresponding instants of preparatory phase (1,2), takeoff (3), flying time (4), and touchdown (5). The gray area corresponds to the weight of the jumper (here, a woman of 43 kg). ECC-RFD, eccentric rate of force development; CON-F, concentric vertical force; TIME, the total duration of the jump; and ECC-T, eccentric phase.

maximized both peak force and peak velocity resulting in maximal power output (27). A Vertec measurement device (Sports Imports, Columbus, OH) was used as an overhead goal for the athlete to ensure motivation by giving feedback to the athletes and maximize trajectory in the vertical plane. The JH was calculated from impulse momentum (19,35).

Force-Time Variables. The independent variables were extracted from the force-time curve and included ECC-RFD, R-ECC-RFD, ECC-T, TIME, ECC-T:T, and CON-F. The ECC-RFD (Newtons per second) was determined during the eccentric phase (Figure 1). This measurement is based on the average slope of the eccentric loading portion of the F-T curve; it begins when force exceeds body weight, ends when velocity comes to zero (bottom of descent when loading for jump). This variable has been calculated as an absolute value (ECC-RFD) and as a normalized value of relative eccentric RFD (R-ECC-RFD) by dividing the value of ECC-RFD by body mass to study the independent mass effect. TIME is the total time of the CMJ and ECC-T the eccentric time. ECC-T:T was calculated as the ratio of ECC-T to TIME. The CON-F in Newton per kilograms was calculated during the propulsive phase of the movement and normalized to body mass. The eccentric phase (ECC) starts when movement begins and ends when athlete is at bottom of loading phase of their jump. The

Table 2. Values of the studied variables (mean and *SD*) for males and females, mean value, and difference.*

	Female	Male	Difference	All	Range
ECC-RFD, $kN \cdot s^{-1}$	3.26 (1.73)	5.12 (2.18)	+36.3†	4.45 (2.2)	0.64–122.2
R-ECC-RFD, $N \cdot s^{-1} \cdot kg^{-1}$	52.91 (24.9)	61 (23.73)	+11.6%†	58.32 (24.2)	11.6–150.8
TIME, ms	502 (10)	500 (10)	+0.4%	500 (9.4)	321–795
ECC-T, ms	223 (5)	214 (4)	+4%	214 (4)	109–571
ECC-T:T, %	43.55 (6.5)	42 (5.4)	+4%	42.3 (5.8)	31.3–66.2
CON-F, $N \cdot kg^{-1}$	19.83 (1.8)	21 (1.82)	+5.75†	20.60 (1.92)	16.02–27.90
JH, cm	42.6 (6.3)	57.9 (7)	+26.4%†	52.44 (9.9)	26.3–84.1

*ECC-RFD = eccentric rate of force development; R-ECC-RFD = relative eccentric rate of force development; TIME = total duration of the jump; ECC-T = eccentric time; ECC-T:T = ratio of ECC-T to TIME; CON-F = relative average vertical force during the concentric phase; JH = jump height.

†Significant gender effect $p < 0.01$.

Table 3. One-way analysis of variance (ANOVA) test post hoc (Fisher-LSD) between sport categories.

	N	JH	TIME	ECC-T	ECC-T:T	R-ECC-RFD	CON-F
Basketball	50	46.8 (12.7)*	494 (13)*	260 (17)*†	49.6 (4)*†	3.37 (0.32)*†	20.85 (0.29)‡
Football	40	50.1 (15.9)†‡	485 (16)§	199 (15)‡§	41.3 (3.3)‡§	4.53 (0.40)‡§	20.5 (0.37)
Volleyball	55	45.7 (11.8)†§	525 (12)*†§	241 (18)†§	46.8 (4.3)†§	3.57 (0.30)†	19.64 (0.27)†§
Baseball	84	59.1 (8.6)*‡§	495 (9)§	198 (13)‡§	40.2 (5)‡§	5.41 (0.22)‡§	21 (0.20)§
ANOVA (F)		37.65	7.95	11.4	12.5	12.45	5.56
p		<0.0001	<0.001	<0.0001	<0.001	<0.0001	<0.01

*Post hoc: difference with football.
†Post hoc: difference with baseball at $p < 0.01$.
‡Post hoc: difference with volleyball.
§Post hoc: difference with basketball.

propulsive (concentric) phase (CON) starts when the displacement reached its lowest value until the force-time curve returned to zero (Figure 1). The dependent variable was the vertical JH, expressed in centimeters.

Statistical Analyses

The analyses were conducted using STATBOX pro 7.2.2 for Excel 2007 (FBC Software, Issy les Moulineaux, France). Pearson correlation coefficients were used to determine the relationships between independent variables and the dependent variable. Descriptive statistics were used to verify that the basic assumption of normality of the dependent variable was met. Tests of normality of distribution and skewdness revealed no abnormal data pattern. To verify the stability of the data for the dependent variable, we calculated the population-specific intraclass correlation coefficient (ICC). Force variables and JH demonstrated very high test-retest correlation (ICC range, 0.92–0.95), whereas time variables demonstrate high test-retest correlations (ICC range, 0.83–0.88). For assessing the gender and the sport group difference, a 1-way ANOVA was performed. An LSD-Fisher post hoc analysis was conducted to detect differences among groups.

A principal components analysis (PCA) was performed on the data obtained from 229 subjects (the 6 jumps were averaged for each subject, and only the 4 groups of main sports were kept for this analysis) to identify the principal components summarizing the 5 variables (only the unloaded force variables have been kept to remove any weight effect). The PCA was obtained from Statbox Pro package (version 5.5) using the procedure described by Kollias et al (28). The number of principal components in the pattern matrix extracted by the PCA was chosen with an Eigenvalue greater than 1 (Kaiser criterion). The original matrix was rotated to extract the appropriate variables, using a normalized VARIMAX rotation (orthogonal rotation). This rotation allowed an earlier labeling of the principal components. To characterize the jumping profiles for each sport group, the individual jumps (averaged over trials) were plotted in a plane containing the 2 principal components. Considering the several number of subjects in the study, the level of significance was set at $p < 0.01$.

RESULTS

Sport-Specific and Gender Results for Biomechanical Variables

Table 4. Correlation matrix among all variables.*

	JH	TIME	ECC-T	ECC-T:T	ECC-RFD	R-ECC-RFD	CON-F
JH	1						
TIME	−0.21†	1					
ECC-T	−0.23†	0.91†	1				
ECC-T:T	−0.23†	0.86†	0.82†	1			
ECC-RFD	0.52†	−0.67†	−0.71†	−0.66†	1		
R-ECC-RFD	0.40†	−0.72†	−0.72†	−0.62†	0.87†		
CON-F	0.57†	−0.69†	−0.44†	−0.05	0.56†	0.55*	1

*JH = jump height; TIME = total duration of the jump; ECC-T = eccentric time; ECC-T:T = ratio of ECC-T to TIME; ECC-RFD = eccentric rate of force development; R-ECC-RFD = relative eccentric rate of force development; CON-F = relative average vertical force during the concentric phase.
†means significant at $p < 0.01$.

Table 2 shows that males jumped 26.4% higher than females (57.9 ± 7 vs. 42.6 ± 6.3 cm). The values of ECC-RFD, R-ECC-RFD, and CON-F were significantly higher (all $p < 0.01$) in males than in females (+36.3%, +11.6%, and +5.75% respectively). The duration of the jump does not differ between both sexes (500 ± 10 vs. 502 ± 10 ms for male and female, respectively) and ECC-T (214 ± 6 vs. 223 ± 5 ms for male and

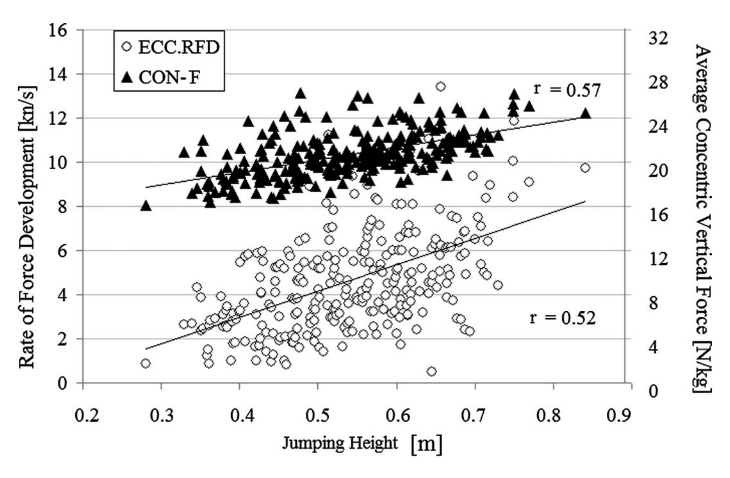

Figure 2. Linear regression model between the best predictive variables for the dependent variable (jumping height). ECC-RFD, eccentric rate of force development (white circles); CON-F, concentric vertical force (dark triangles).

female, respectively) and ECC-T:T (42 ± 5.4 vs. 43.55 ± 6.5% for male and female, respectively). Moreover, the values of JH were significantly different ($p < 0.01$) between groups. Furthermore, the post hoc shows that Baseball players achieved the highest JH than other participants and football players highest JH than volleyball and basketball players (Table 3).

Correlation Study and Principal Component Analysis. Concerning the matrix of correlation (Table 4), all variables were significantly correlated with JH, with low to moderate coefficients ($r = 0.21$–$r = 0.57$) and with negative values for all time variables. The best predictor variables are summarized in Figure 2.

The correlation matrix (Table 4) shows that all the studied variables are correlated, and so a PCA could be performed. This PCA revealed 2 principal components, characterized by a time component and a force component that accounted for 76.8% of the total variance. The commonalities, which measures the percent of variance in a given variable explained by all the factors jointly, ranged from 0.74 (R-ECC-RFD) to 0.97 (CON-VF) revealing a high reliability of the indicator and the model found as well.

The first principal component that was rotated, accounting for 53.8% of the total variance, was associated with time variables. The Eigenvalue corresponding to this component was 2.69. This component linked TIME to ECC-T with high and positive loading (0.960 and 0.957), respectively, indicating that a long contact time is associated to a long eccentric time.

The second rotated principal component accounted for 23% of the variance of the force data. The Eigenvalue of this second component was 1.14 and was associated with the force variables and ratio time. This force component linked together R-ECC-RFD, CON-VF, and ECC-T:T with loadings of 0.602, 0.480, and −0.944, respectively. The positive loading indicates that a high value of R-ECC-RFD was associated with a high value of maximum ground reaction force and a low value of ECC-T:T.

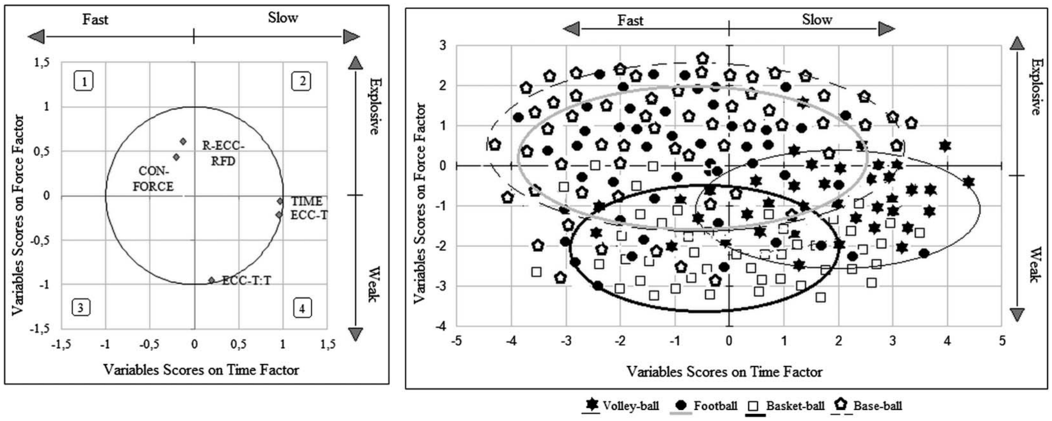

Figure 3. The left part represents the variable scores on the 2 rotated principal components. The right part represents the individual scores for each subject. ECC-RFD, eccentric rate of force development; CON-F, concentric vertical force; TIME, total duration of the jump; ECC-T, eccentric phase and ECC-T:T is the ratio time. ✱ volleyball; ● football; □ basketball; ✿ baseball.

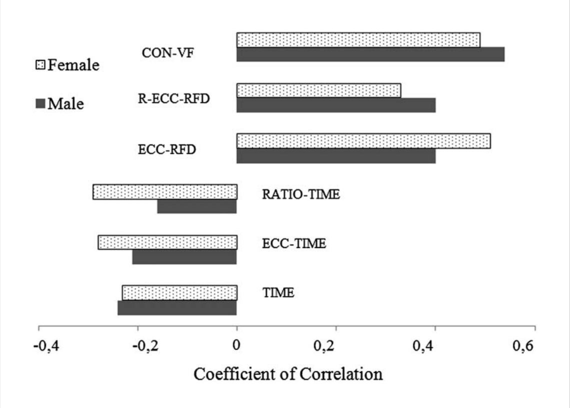

Figure 4. Comparative coefficient of correlation between male and female on the force-time variables studied. ECC-RFD, eccentric rate of force development, CON-F the concentric vertical force; TIME, total duration of the jump; and ECC-T, eccentric phase and ECC-T:T the ratio of ECC-T on TIME. All variables are significantly correlated with the vertical performance ($p < 0.01$).

The second goal of the PCA analysis was to describe the force pattern strategy differences among different sport group samples. Four sport groups were tested and contrasted. Plotting the mean individual scores on the 2 principal components allowed this comparison (Figure 3). The *x*-axis of the right part of Figure 3 corresponds to the first principal component, namely the time component. Figure 3 can be separated into 4 parts. The right side of the figure indicates a high value of the time component, meaning a long contact and eccentric time, therefore a slow jumping profile. Volleyball players are characterized by this profile with component score ranging from −2 to 4.5. The ANOVA confirms this analysis by showing a large effect of TIME between volleyball players and the 3 other sport groups ($p < 0.001$). The left side corresponds to a negative value of the *x*-axis, i.e., a short time and eccentric time, revealing a fast jumping profile, as illustrated by several football and baseball players (score ranging between −4.5 and 3). The top of the Figure 3 corresponds to a positive value of the *y*-axis (force component) revealing a high value of R-ECC-RFD and CON-VF, i.e., an explosive jumping profile. Football and baseball players exhibited such a profile (scores ranging from −1.5 to 2.8), with higher values of R-ECC-RFD than volleyball and basketball players ($p < 0.001$), In comparison, the bottom of the figure corresponds to a negative value of the *y*-axis revealing weak values of R-ECC-RFD and CON-VF and a high ratio of eccentric time on total time. Basketball revealed such a profile with component scores ranging from 0 to −3.5. This plotting defines 4 different profiles of jumper (1: fast and explosive to 4: slow and weak).

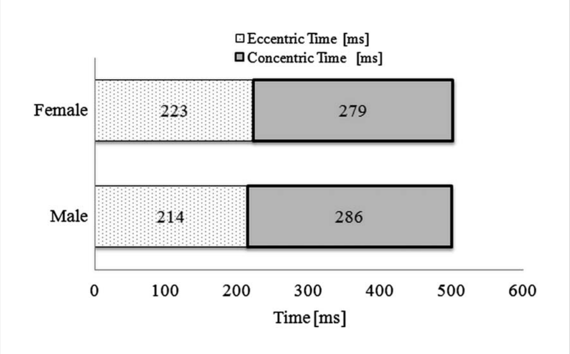

Figure 5. Comparative temporal structure (eccentric and concentric phase) between male and female in countermovement jump.

DISCUSSION

The first goal of the present study was to assess the predictability of selected variables extracted from the F-T curve. All the recorded variables were significantly correlated with JH ($p < 0.01$). The time variables explain less than 10% of the total variance, whereas the force variables explain 27–32% of the variance.

The novelty of the present study is that with this alternative method of looking at average ECC-RFD, maximal JH in CMJ is shown to highly correlate with this variable when calculated as an absolute value (ECC-RFD, $r = 0.52$, $p < 0.001$) and additionally when normalized to body mass (R-ECC-RFD, $r = 0.40$, $p < 0.001$).

Several studies have failed to find such a strong link between ECC-RFD and vertical jumping performance (20,26,34,36,46). The difference in these results could be explained by 4 key differences in their methodological approach. First, the present study measured JH while simultaneously recording RFD during CMJ on a force-plate, contrary to previous studies. Second, the method to measure the vertical performance is more accurate in the present study (impulse method) than with the flight-time method, which is associated to high errors (19,26) due to the variation in the take-off and the landing position. Third, the choice of recording the average eccentric RFD rather than peak eccentric RFD which is more conventionally used, identifies what happens throughout the entire eccentric loading phase, as opposed to just the highlight that peak measurements tend to give us. This point will be discussed further. Finally, several studies did not use arm swing (20,46), which is a more natural and functional approach that allows an increase in jumping performance (17,22,31,44). In all the studies where arm swing was not used (20,21,27), results did not find correlations between RFD and JH.

Only 1 study to date (McLellan et al. (37)) has found a positive and significant correlation between the maximum value of the rate of force and the JH ($r = 0.68$), and that study proposed a similar protocol than the one used in the present study (using 3 of the 4 aspects discussed above).

The present study is the first one that demonstrates that ECC-RFD is a stronger and more accurate predictor of JH than peak concentric RFD because it summarizes the capacity of the muscle-tendon unit structure to stretch quickly before attaining the peak of force. Only 2 studies have used ECC-RFD as a predictive tool. Earp et al. (14) studied the effect of muscle-tendons architecture on the rate of force development calculated during the very beginning of the jump (eccentric phase). They found that the gastrocnemius fascicle length had an intensity-dependent relationship with RFD, serving to positively predict RFD during early CMJs. In another study, Jensen and Ebben (24) recorded the eccentric RFD during different plyometric jumping tasks, but without investigating a link with the JH. They show that ECC-RFD is different among the jumps and the plyometric constraints as well. The method used to measure ECC-RFD in the latter article (between the first peak of GRF divided by the time from onset of landing force to the first peak of GRF) is quite different than in the present one (averaged along the eccentric phase), resulting in higher values of ECC-RFD in our study. In addition, researchers have suggested that a threshold for ECC-RFD is necessary to attain to optimally activate the SSC (15).

The second goal of this study was to compare the way males and females jump. First, male jumps were 15.3 cm (+26.4%) higher than female jumps. This difference is slightly higher than those found in literature, where values ranged between 10.6 and 11 cm (3,33,44,45). This finding likely occurred because our sample is highly trained, and the values of JH are higher, and therefore their differences as well. This difference could be explained by higher values of ECC-RFD (+36.3%) in males than in females. When normalized to body mass, R-ECC-RFD is 11.6% higher in males than in females, showing that the difference in body mass is not purely enough to explain the difference in values even if it minimizes the effect (1.5 times higher in absolute value vs. 1.2 times higher in relative value). Thus, this shows a higher capacity to accelerate their body when performing a CMJ. To our knowledge, there are only 2 studies that have investigated lower-limb gender difference in RFD (1,15). In the first one, the RFD was assessed by using maximum voluntary isometric contractions for the knee extensors, and the authors found that men demonstrated approximately 1.5–2.0 times higher RFD than women. In the second study, RFD was assessed during the concentric phase of a CMJ with arm swing but no difference was found in RFD between skilled athletes. The present study reveals that men demonstrated approximately 1.5 times higher RFD than women (1.2 when normalized to body mass). This differs to the results of the aforementioned study (15), which is probably because of a difference in the calculation method of RFD.

Previous reports suggested that the lower RFD observed in women, compared with men, may be the result of structural differences in the muscles elastic properties (30). Indeed, the gender differences in RFD of a CMJ are probably related to the differences between men and women in body dimensions and muscle architecture, which influence the way force is produced between the 2 genders (e.g., disparities in tendon length, angle of pennation, and fascicle properties) (2). Despite these structural gender differences, the significance of muscle mass does still explain part of this difference in jumping performance because JH discrepancies between the 2 genders does decrease when RFD is normalized to body mass (1.5 times higher to 1.2 times higher). Furthermore, the previously mentioned study (2) revealed higher pennation angles in males than in females of the vastus lateralis (15.8° vs. 14.1°) and the gastronemius medialis (26° vs. 24.5°) and longer fascicles in the vastus lateralis in men and gastrocnemii in women, which where concluded to impact on jump performance (3).

The Figure 4 shows the difference in correlations for each variable between males and females. Few differences have been noticed. The eccentric-time seems to have a better link with JH for women ($r = -0.28$ vs. -0.21) and consequently, the ratio as well ($r = -0.29$ vs. -0.16). Regarding the force variables, better correlations have been found in males than in females in R-ECC-RFD ($r = 0.42$ vs. 0.35) and in CON-F ($r = 0.59$ vs. $r = 0.50$). These slight differences show that better jump performances within the genders are obtained by minimizing the key time variables in women while maximizing the key force variables in men, and implies that different muscular architecture could be the fundamental influence in differing JHs between the genders (3,30).

Despite these differences, another major result of this study was that the temporal structure of the jump is the same. Indeed, the ECC-TIME (223 ± 5 for men vs. 214 ± 6 ms for women, the TIME (502 ± 10 for men vs. 500 ± 10 ms for women) and the RATIO-TIME (43.5% for men vs. 42% for women) were similar, showing that the kinematics are highly comparable, as previously shown during CMJ (43) and DJ (33). This similar temporal structure (Figure 5) highlights that the motor patterns are comparable between males and females. So, the temporal structures are quite similar, but the difference of muscular architecture and structural dimensions like muscle thickness and size (3) allows men to provide a higher level of force by increasing the ECC-RFD during the same time. This means that men are perhaps able to more efficiently stretch their muscles by using larger angular displacements of the knee, hip, and ankle joints during a time compatible with the short stretch shortening cycle (less than 250 ms in eccentric phase), as previously described (40). The shorter duration allows for elastic energy to be stored in muscles and tendons during a preload (stretch) and then applied to a resulting contraction (shortening).

The third goal of this study was to explain the links between variables, using a PCA analysis. The accuracy of the PCA model found (76.8% of the JH variance) is in accordance with previous ones using the same statistical approach during vertical jumping in men (28,32) with percentages ranging from 74.1 to 78.8. Our model revealed 2 components: a time component and a force component.

The *x*-axis on Figure 3 corresponds to the first component, namely the time component. This component includes TIME and ECC-T, assuming that an increase in the time to peak force is linked to an increase of total time. When comparing our PCA model to previous models, during the 1-legged vertical jump (32) and squat jump (28), many similarities and few differences have been observed. First, the 2 components share similar mechanical characteristics, such as a time and a force component. The time component linked TIME and ECC-T for these 3 kinds of jump, but RFD was associated with this component for squat jump but not with the force component. This reveals the similarities between 1-legged vertical jump and CMJ, which both allow the jumper to stretch the muscles and tendons during the eccentric phase of jump, whereas squat jump does not allow such a beneficial pre-load.

The *y*-axis on Figure 3 corresponds to the second component, namely the force component. It links the force variables with positive loadings and the time ratio with negative loading. In other terms, the higher the RFD, the higher the ground reaction force and the smaller the time ratio. Therefore, this model very efficiently captures the fact that a high value of ECC-RFD allows an increase in the level of force (11) by rapidly recruiting motor units (12) through a higher preload and enhanced interaction between contractile and elastic elements by storage and utilization of elastic energy and activating the stretch reflex (7,9,12,16). Our PCA model is comparable to previous ones, especially to the 1-legged vertical jump (32) that linked RFD to CON-F. But the novelty of the present study is that the ratio of time has a main role on this force component, which has never been demonstrated before (to the best of our knowledge). The negative score of ECC-T: T on this force component shows that the ratio of time, i.e., the time available to develop force during the ECC phase on the total impulse time, is a crucial factor in allowing the activation of stretch reflex (6,8,11,16). In other terms, minimizing this time ratio increased the rate of force development and the ground reaction force in an explosive manner.

The final purpose of the present study was to investigate whether inherent demands of a particular sport have a relationship with certain force-time variables. If so, these trends could therefore be labeled "sport specific (force-time) signatures."

First, JH performance is higher for outdoor team sports than for indoor sports, with values ranging from 59.1 ± 8.6 cm for baseball players to 46.8 ± 12.7 cm for basketball players ($p < 0.0001$). Second, the individual PCA plotting revealed different profiles of jumpers depending on their sporting background. The indoor team sports (basketball and volleyball) revealed negative scores on the force component and high scores for volleyball players on the time component. Outdoor team sports such as football and baseball, revealed an explosive profile, with high scores on the force component. This slow profile for volleyball players, and to a slightly lesser extent Basketball (Figure 3), is because of the specificity of the jumping actions involved during competition. Volleyball does not involve a direct and physical confrontation with the opponent but a complex optimal requirement to time the jump to be at the highest point of the parabola at the right time to attack the ball. This method of force application is only possible during the ground contact phase of the jump so this therefore requires development of force throughout a longer period of time when compared with sporting skills where ground contact times are typically shorter because of the smaller response times typically found in the outdoor sports of football and baseball. The time available to reach maximum JH is much greater in volleyball (525 ± 12 ms; $p < 0.001$) compared with other sports. This result is in accordance with Laffaye et al. (32) who discovered time-dominant profiles in volleyball players who performed 1-legged vertical jumps.

The game of basketball involves a lot of jumping in a constrained environment, often requiring time-dominant jumping actions in reaction to an open but small court of opponents. Examples of these movements are when feinting at an opponent through the use of multiple eccentric phases of a jump (loading then braking), and also, then often having to maximally accelerate through a prolonged concentric phase of a jump to out-jump an opponent, yet without the benefit of a quick preload. This behavior is very well captured by the PCA model, which shows high negative scores on the force component, which in turn are characterized by a high ratio of eccentric time to total time in basketball (49.6 ± 4) and Volleyball (46.8 ± 4.3), a variable we have found to be higher in those aforementioned indoor sports when compared with the outdoor team sports studied (baseball: 40.2 ± 5 and football: 41.3 ± 3.3).

Finally, football and baseball players tend to display explosive profiles, with high values of R-ECC-RFD and CON-FORCE. It is interesting to notice that these 2 sports have the higher values of JH (50.1 ± 15.9 cm and 59.1 ± 8.6 cm, respectively), confirming the strong link between force, rate of force, and jumping performance (13,37,38). When compared with the other sports tested, football and baseball are not primarily characterized by repetitive jumping actions during competition, but require more maximal rested explosive muscular actions, such as pitching, sprinting, or tackling within short time frames. This could mean that the force component is dependent on muscle-tendon system properties, regardless of the direction of the ground reaction force (39).

The present study highlights the role of average eccentric RFD on JH. The PCA has linked this force-time variable with the relevant time ratios, and subsequent JHs to clearly indicate that the depth of the load during a jump plays a major role in JH. Lowering the center of mass could be useful only under the condition that the ratio of the eccentric time on the total time is low (<42%) and by taking into account, first, the gender difference because of the difference in muscular architecture, and finally, the sport-specific differences because of the inherent demands of the athletic requirements.

PRACTICAL APPLICATIONS

The present study has 3 main applications for practice. The first one is that a valid method to increase vertical performance or JH is to increase one of the predictive factors. Indeed, increasing CON-F (13,38,41,42) or ECC-RFD could perhaps change musculotendinous properties and increase the vertical velocity at take-off. Specifically, minimizing the eccentric phase and utilization of the resultant speed of stretch, contribute to improved stretch-shorten cycle performance after training (11) by altering muscular architecture, such as pennation angle or fascicle length (3,4) and/or through neuromuscular adaptations specific to the training program.

The second practical application is highlighted by the link between the time ratios on the force variables. The PCA model implies that decreasing the time ratios, meaning shortening the eccentric time of jump without changing the total time, increases the values of the force variables and the performance as well. This implies that advice could be given during jumping tasks (drop jumping, CMJs) to decrease the eccentric time to increase performance Finally, the use of biofeedback devices for jumping could be a good and rational way to increase the stretch shortening cycle to become more explosive, by using a criterion of time ratios. Based on the present study, a threshold of 42% makes the difference between good jumpers (JH $>$ 50 cm) and average jumpers (JH $<$ 50 cm).

Finally, the sporting requirements have to be taken into account in the athletes training program because the exact athletic demands and, more specifically, the force-time profiles are not comparable between the sports analyzed in this study. These findings reveal a time-prevailing profile for basketball and volleyball players and a force-prevailing profile for football and baseball players. Consequently, trainers should focus on the need to adapt jumping/plyometric programs to the time requirements of the tasks presented in indoor jumping team sports, whereas as a greater focus is required to increase explosive force for dynamic outdoor sports such as football and baseball.

This might imply an individual training program based on the analysis of 1 of the force-time variables, as these qualities are fundamental elements that influence sprinting, bounding, or any activities that require ground reaction force.

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