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Influence of countermovement depth on net force, push-off time, vertical impulse and performance during jumping

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ABSTRACT

The purpose of this study was to investigate the influence of push-off distance on maximal jump height and to characterize the relationships between vertical jump mechanical parameters. Seventeen CrossFit athletes performed maximal countermovement jumps on two force-plates, with four different push-off distances induced by different countermovement depths. Results confirmed that push-off distance and maximal jump height were related by a quadratic relationship, and that exists an individual push-off distance maximizing maximal jump height. Furthermore, the increase in push-off distance was associated with an increase in the time of push-off and a concomitant decrease in the mean vertical external force, changing the relative net vertical impulse and so maximal jump height. An almost perfect negative linear relationship was observed between mean vertical external force and time of push-off ($r = -0.99$, $p = 0.006$), mathematically resulting in a quadratic relationship between relative net vertical impulse and time of push-off ($r = 1.00$, $p < 0.001$). This negative linear relationship could be explained by changes in joint angles and velocities associated with an increase in push-off distance, modifying joint torque production capacities during vertical jumping. This provides new insights to characterize vertical jump mechanical parameters and ways to optimize training and jump performance.

1. Introduction

Vertical jump height is considered a significant predictor of performance in numerous sports (e.g., football, basketball, volleyball) (Dal Pupo et al., 2012). Therefore, improving the maximal vertical jump height of athletes is an important goal for coaches or conditioning professionals.

In order to maximize vertical jump height, many studies have investigated the influence of vertical push-off distance (h_{PO}), i.e., squat or countermovement depth, on maximal jump height (h_{max}). When testing different h_{PO} conditions, authors revealed a varying effect of h_{PO} on h_{max} . While some studies reported an increase in h_{PO} is beneficial for jump performance (improved h_{max}) (Gheller et al., 2015; Kirby et al., 2011; McBride et al., 2010; Sánchez-Sixto et al., 2018), other studies found that an increase in h_{PO} results in an unchanged h_{max} (Domire and Challis, 2007; Mitchell et al., 2017; Pérez-Castilla et al., 2021; Petronijevic et al., 2018; Selbie and Caldwell, 1996). These discrepancies have been suggested to be linked to morphological characteristics of the

population (e.g., body size or segment length), inter-individual variability in maximal joint range of motion, familiarity with the movement task, differences in training background or level, intersegmental coordination patterns, and specific movement execution instructions (Gheller et al., 2015; Markovic et al., 2014; Sánchez-Sixto et al., 2018). Moreover, these results can be explained by the quadratic relationship observed between h_{max} and h_{PO} (Mandic et al., 2015; Mitchell et al., 2017), which implies the existence of an optimal h_{PO} maximizing h_{max} (vertex of the relationship). Consequently, it is possible to observe no difference between two measured h_{max} if both lie on either side of the vertex of the relationship, or to highlight a difference by comparing the vertex with a non-optimal condition. However, the position of the conditions tested according to the h_{max} - h_{PO} relationship is generally uncontrolled.

To better understand the influence of h_{PO} on h_{max} , some previously cited authors also compared vertical net impulse (VI) values obtained from different h_{PO} . During push-off, individuals must accelerate their body to reach the highest take-off velocity (v_{TO}), and thus the highest

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h_{\max} (Samozino et al., 2010). According to Newton's second law of motion, v_{T0} is directly dictated by the mechanical impulse generated in the direction of the movement (McBride et al., 2010; Winter, 2005). Authors concluded that VI , relative to moving mass (body mass + additional mass, if any), is a strong predictor of jump height, independent of h_{pO} and loading conditions, due to their mathematical relationship (Kirby et al., 2011; McBride et al., 2010; Winter, 2005). Studies have also reported that an increase in h_{pO} results in an increase in VI (Gheller et al., 2015; Kirby et al., 2011; McBride et al., 2010; Salles et al., 2011).

During vertical jump, VI is the integration over time of the net vertical force (ground force reaction minus weight), which corresponds to the product of mean net vertical external force (\bar{F}_{net}) and force application time (corresponding to push-off time, t_{pO}), both of which are influenced by h_{pO} . Domire and Challis (2007) reported that, as expected, t_{pO} increases with the increase in h_{pO} . Some studies manipulating different h_{pO} reported that a higher h_{pO} (and so a higher t_{pO}) induced an increased VI (Sánchez-Sixto et al., 2018; Kirby et al., 2011; McBride et al., 2010). Conversely, several studies reported that an increase in h_{pO} results in a decrease in force production variables (Amasay and Suprak, 2022; Gheller et al., 2015; Kirby et al., 2011; Mandić et al., 2015; Petronjevic et al., 2018; Sánchez-Sixto et al., 2018). Most of these studies focused on peak force (F_{peak}) values and showed that F_{peak} decreased as h_{pO} increased. However, Kirby et al. (2011) reported that F_{peak} is a poor predictor of jump performance when h_{pO} varies. \bar{F}_{net} , being a term of VI mathematical expression, appears as a stronger predictor of jump performance, especially when considering different h_{pO} and loading conditions (McBride et al., 2010). Only one study calculated \bar{F}_{net} and reported that \bar{F}_{net} decreased as h_{pO} increased (Sánchez-Sixto et al., 2018). This decrease in \bar{F}_{net} could be partly explained by torque-angle relationships (Anderson et al., 2007). Starting from a lower position, i.e., higher h_{pO} , can generate a longer time spent (due to lower speed) at non-optimal angles (lower force production). In this case, time spent at optimal angles of force production will be shorter, which may ultimately lead to a reduction in total impulse. A higher h_{pO} could lead to changes in joint angular velocities, neuromuscular activation and intersegmental coordination which may also contribute to the decrease in \bar{F}_{net} (Babault et al., 2003; Gheller et al., 2015).

Considering all of these elements, it appears that h_{\max} directly depends on VI , which is determined by \bar{F}_{net} and t_{pO} , both influenced by h_{pO} in different ways (the effect of h_{pO} on \bar{F}_{net} remaining unclear). However, to date, none of the studies that investigated VI while varying h_{pO} examined the change in \bar{F}_{net} and t_{pO} , the subcomponents of VI . Enhanced understanding of the influence of h_{pO} on VI and its determinants could improve the understanding of mechanisms underlying the existence of an optimal h_{pO} that maximizes h_{\max} .

The current study aimed to investigate the influence of h_{pO} on mechanical parameters of vertical jump and to characterize the relationships between these parameters. We hypothesized that the increase in h_{pO} induces a change in h_{\max} and VI due to changes in \bar{F}_{net} and t_{pO} that we assumed to be associated with a negative linear relationship.

2. Materials and methods

2.1. Participants

An a priori sample size estimation was computed for correlation analysis in G power software. Assuming a normal distribution, to detect a very large effect size $r = [0.7-0.9]$ with a significance level of 0.05 and a statistical power of 0.90, a sample size between 14 and 23 participants was needed.

Seventeen CrossFit athletes (three women) participated in this study (age: 27 ± 7 years, height: 176.5 ± 9.7 cm, mass: 78.2 ± 12.9 kg; squat 1RM: 129 ± 31 kg). All participants had a strength-training background of at least 2 years, trained 9 h/week and were free of injuries prior to

testing. Additional prerequisites for participation in the study were regular involvement in explosive training and proper and consistent execution of maximal countermovement jump (CMJ) with and without additional load whatever the countermovement depth condition. CrossFit athletes were selected as the study population due to the emphasis on explosive movements and the manipulation of varying loads in their training routines, which supports their ability to handle loads up to 70 %1RM, a key requirement for the larger project to which this study contributes. Participants were informed about the procedure of the study, and signed a written informed consent. This study design was approved by the local ethics committee of Nantes University (reference number: 07062022).

2.2. Data collection procedures

The current study is part of a larger project requiring participants to perform multiple CMJs combining two conditions: depth of the countermovement (four) and load (six). To ensure participants could perform all jumps without fatigue, only one jump was asked per condition. Considering the study objective, we focused exclusively on unloaded jumps.

Participants reported to the laboratory for a single session. They were required to avoid any intense physical activity 48 h prior to the testing session to minimize the potential impact of the previous training activities on measurements. The testing session took place at the participant's usual training time. Upon arrival, anthropometric parameter measurements were collected. Afterwards, the maximal countermovement distance was measured as the difference between the barbell vertical position at standing position and the maximal countermovement depth position. Maximal countermovement depth was divided into four conditions: 0–30 %, 30–50 %, 50–70 % and 70–100 %, expressed in percentage of maximal countermovement depth (0 % = standing position, 100 % = maximal countermovement depth). The vertical position of visual cues placed on either side of the participant was manipulated according to the depth condition to indicate the target depth for each CMJ. These depth conditions were used as targets to experimentally manipulate h_{pO} , but not for data processing. Next, all participants performed a standardized warm-up consisting in 10-min on a cycle ergometer and 10-min of lower limb joint mobility exercises, which was followed by submaximal unloaded and loaded CMJs at different countermovement depths (thanks to visual targets) to become familiarized with the depth conditions used during testing. After warm-up and familiarization, participants performed one maximal CMJ at each depth condition in a randomized order (4 maximal CMJs in total). Each trial was followed by a 2-min rest period for complete recovery. The use of randomized order and 2-min rest period was intended to limit fatigue and its potential influence on the h_{pO} - h_{\max} relationships.

For each CMJs, participants were asked to place their feet at the exact same location (thank to tape placed on the force plates). Participants were instructed to hold a weightless (plastic) barbell across their shoulders with the same hand position and keep a horizontal look throughout the CMJ to restrict any arm, head or trunk movement and reduce the force gains associated with trunk action. Participants were asked to perform the eccentric phase of the CMJ as quickly as possible while still reaching the target depth and then to quickly switch to the concentric phase of the CMJ without downtime. Before each trial, participants were vocally informed of the expected depth conditions. They were also reminded that the main goal was to achieve maximal jump height. The barbell vertical position at the end of the eccentric phase was required to match the corresponding depth. In the rare cases where CMJs did not meet the expected depth conditions, trials were neglected and repeated.

A set of 49 retroreflective spherical markers (14 mm) were fixed on body landmarks of all participants (Begue et al., 2021). Three markers were attached at the middle and both extremities of the barbell. A motion capture system equipped with 10 cameras (4 Miquis and 6 Oqus

cameras, Qualisys, UK) and one force-plate located under each participant's foot (Type 9286BA, Kistler Instruments Inc, Switzerland) were synchronized using an analysis software (Qualisys Track Manager, v.2020.2, Qualisys, UK) to simultaneously collect kinematic and ground reaction force (GRF) data at 200 Hz and 1000 Hz, respectively.

2.3. Data analysis procedures

Kinematic and GRF data were low-pass filtered using a zero lag fourth order Butterworth filter with a cut-off frequency of 12 Hz. Knee angles in the sagittal plane were calculated from kinematic data of joint markers located bilaterally on the lateral femoral epicondyles, greater trochanters and lateral malleoli. Vertical displacement of the barbell was obtained from kinematic data of the marker located at the middle of the barbell.

The push-off phase started when vertical displacement of the barbell turned positive and ended when the GRF signal fell under 10 N. t_{pO} corresponded to the elapsed time of the push-off phase. Instantaneous net vertical external force was obtained by removing the body + bar weight from the GRF signal. Instantaneous vertical velocity of the body center of mass (CM) during push-off was computed by integration of CM vertical acceleration over time. The integration constant was set to zero because of the null starting velocity. Mean vertical net external force (\bar{F}_{net}), vertical velocity of the CM and power (\bar{P}) for each trial were all obtained by averaging the instantaneous net vertical external force, vertical velocity and power over the entire push-off phase. \bar{F}_{net} and \bar{P} were then divided by the participant's body mass to give relative mean vertical net external force and relative mean power. v_{TO} corresponded to the instantaneous velocity at the instant of take-off. VI was obtained by integrating over time the net vertical GRF of the push-off phase using the trapezoidal method. VI was then divided by the participant's body mass to determine relative VI . Instantaneous vertical position was obtained during push-off by integration of vertical velocity over time. h_{max} was calculated as the difference between the highest vertical position of the CM reached during the CMJ and the vertical position of the CM at take-off. h_{pO} was computed as the difference between the vertical position of the CM at take-off and the vertical position of the CM at the beginning of the push-off phase (the lowest position of the CM during the countermovement). h_{pO} was then expressed as a percentage of the individual's maximal push-off distance.

2.4. Statistical analysis

Descriptive statistics are presented as mean \pm standard deviation (SD). Normality of the dataset was checked using the Shapiro-Wilk test and visual inspection of Q-Q plots before analysis. Based on the literature (Mandic et al., 2015; Sánchez-Sixto et al., 2018), linear regression (relative \bar{F}_{net} - h_{pO} , relative \bar{F}_{net} - t_{pO} and t_{pO} - h_{pO}) and quadratic regression (h_{max} - h_{pO} , relative VI - h_{pO} and relative VI - t_{pO}) analyses were applied to explore the relations between vertical jump mechanical parameters on both averaged (mean values of all participants) and individual data. Pearson's correlation coefficient (r) was reported to characterize the relation between these parameters. The magnitude of the correlation was assessed with the following thresholds: <0.10 , trivial; 0.10 to 0.30 , small; 0.30 to 0.50 , moderate; 0.50 to 0.70 , large; 0.70 to 0.90 , very large; and 0.90 to 1.00 , almost perfect. (Hopkins et al., 2009). Statistical analyses were performed using SPSS 21.0 software (IBM, USA), and the significance level was set at $p < 0.05$.

3. Results

Mean \pm SD values for mechanical parameters across different push-off distances are presented in Table 1. Typical vertical force and vertical velocity vs. vertical position of the CM obtained during countermovement jumps performed across different h_{pO} are illustrated in Fig. 1.

Table 1

Mean \pm SD of the mechanical parameters across different countermovement depth conditions.

Mechanical parameters	Countermovement depth conditions			
Push-Off Distance (%)	26.1 \pm 2.8	39.6 \pm 6.1	60.7 \pm 5.7	76.5 \pm 4.3
Push-Off Distance (m)	0.23 \pm 0.02	0.31 \pm 0.05	0.45 \pm 0.07	0.57 \pm 0.08
Maximal Knee Angle ($^{\circ}$)	60 \pm 11	70 \pm 8	89 \pm 10	103 \pm 8
Maximal Jump Height (m)	0.18 \pm 0.04	0.25 \pm 0.06	0.28 \pm 0.05	0.32 \pm 0.08
Vertical Impulse (N.s)	147 \pm 21.9	170 \pm 29.7	184 \pm 36.5	199 \pm 47.9
Relative Vertical Impulse (N.s.kg $^{-1}$)	1.87 \pm 0.22	2.20 \pm 0.27	2.34 \pm 0.22	2.49 \pm 0.3
Push-off Time (s)	0.165 \pm 0.012	0.209 \pm 0.037	0.312 \pm 0.056	0.368 \pm 0.051
Take-Off Velocity (m.s $^{-1}$)	1.87 \pm 0.22	2.20 \pm 0.27	2.34 \pm 0.22	2.49 \pm 0.3
Mean Velocity (m.s $^{-1}$)	1.36 \pm 0.09	1.48 \pm 0.14	1.46 \pm 0.13	1.54 \pm 0.17
Mean Net Force (N)	893 \pm 195	835 \pm 200	611 \pm 188	546 \pm 149
Relative Mean Net Force (N.kg $^{-1}$)	11.3 \pm 1.41	10.8 \pm 2.02	7.8 \pm 1.77	6.9 \pm 1.27
Mean Power (W)	1884 \pm 349	2048 \pm 436	1845 \pm 479	1896 \pm 523
Relative Mean Power (W.kg $^{-1}$)	24 \pm 3.3	26 \pm 4.3	23 \pm 3.9	24 \pm 4.1

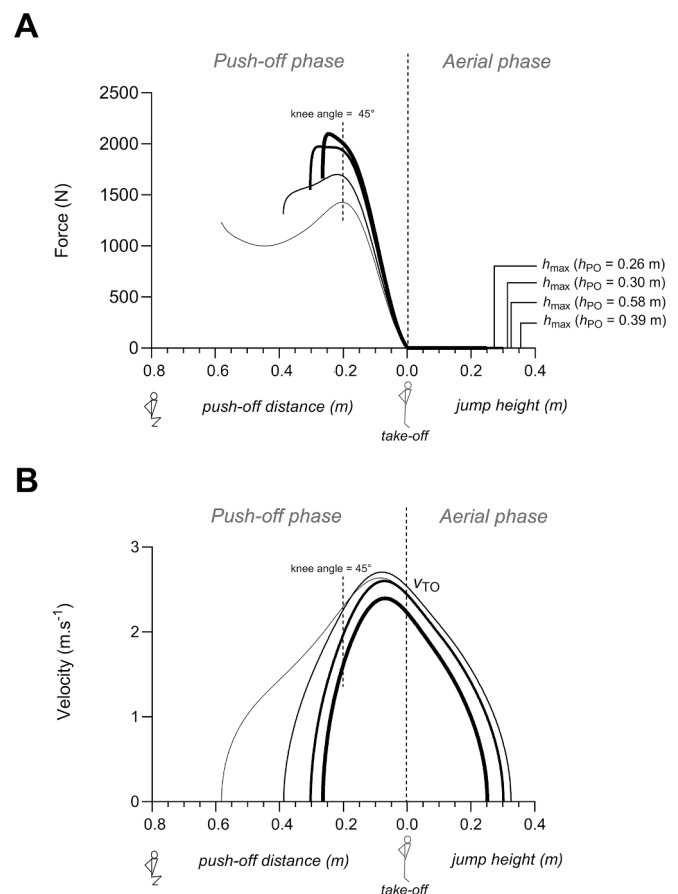


Fig. 1. Typical vertical forces (Panel A) and vertical velocities (Panel B) vs. vertical position of the centre of mass obtained during countermovement jumps performed across different push-off distances (h_{pO}) for a representative subject. As illustrated, jumping with different h_{pO} modifies the velocity reached at a given knee angle (e.g., 45°), inducing changes in force production.

The mean regressions performed between h_{PO} or t_{PO} and the mechanical parameters, including the respective equation models and goodness-of-fit parameters, are presented in Fig. 2. h_{max} and h_{PO} averaged data are related by an almost perfect quadratic regression ($r = 1.00$, $p < 0.001$). When performed on individual data, h_{max} - h_{PO} quadratic regressions presented r values ranging from 0.94 to 1.00 (almost perfect) with p -values ranging from 0.000 to 0.050. Only one participant did not fully reach the significance threshold ($p = 0.057$) despite a correlation coefficient of 0.99. Relative \bar{F}_{net} and h_{PO} averaged data are related by an almost perfect negative linear relationship ($r = -0.99$, $p = 0.005$) as were also observed on individual data ($r = [-0.95-1.00]$, $p = [0.003-0.050]$). t_{PO} and h_{PO} averaged data are related by an almost perfect positive linear relationship ($r = 1.00$, $p < 0.001$) as were also observed on individual data ($r = [0.97-1]$, $p = [0-0.050]$). Relative VI and h_{PO} averaged data are correlated by an almost perfect quadratic relation ($r = 1.00$, $p = 0.001$). When performed on individual data, quadratic regressions presented r values ranging from 0.94 to 1 (almost perfect) with p values ranging from 0 to 0.048. Only one participant did not present a significant regression between relative VI and h_{PO} ($r = 0.94$, $p = 0.057$). Relative \bar{F}_{net} and t_{PO} averaged data are related by an almost perfect negative linear relationship ($r = -0.99$, $p = 0.006$) as were also observed on individual data ($r = [-0.96-1.00]$, $p = [0.001-0.040]$). Only one participant did not present a significant regression between relative \bar{F}_{net} and t_{PO} ($r = -0.99$, $p = 0.086$). Relative VI and t_{PO} averaged data are related by an almost perfect quadratic relationship ($r = 1.00$, $p = 0.001$). When performed on individual data, quadratic regressions presented r values ranging from 0.89 to 1 (very large to almost perfect) with p values ranging from 0.000 to 0.040. Three participants did not present significant regression between relative VI and t_{PO} ($r = [0.79-0.85]$, $p = [0.060-0.560]$).

Regression analysis results between h_{PO} and h_{max} and between h_{PO} and relative VI for two typical participants are illustrated in Fig. 3.

Individual optimal h_{PO} that corresponded to maximal jump performance (the vertex of the quadratic relationship) ranged from 49 to 125 % (100 % being the maximal participant push-off distance). Optimal h_{PO} ranged from 76 to 144 % for individual data, with mean optimal h_{PO} being 75 ± 21 % related to a knee angle of $103 \pm 21^\circ$. Individual optimal h_{PO} that corresponded to maximal relative vertical impulse ranged from 49 to 115 %. Corresponding knee angle ranged from 76 to 135° . Mean optimal h_{PO} was 71 ± 17 % corresponding to a knee angle of $100 \pm 16^\circ$. A linear regression performed between the individual optimal h_{PO} obtained from the quadratic relationship between h_{PO} and h_{max} and the optimal h_{PO} obtained from the quadratic relationship between h_{PO} and relative VI revealed the existence of an almost perfect positive linear relationship ($r = 0.98$, $p < 0.001$).

4. Discussion

The aim of this study was to investigate the influence of push-off distance on the mechanical parameters of vertical jump, and to characterize the relationships between these parameters. Our primary hypothesis was that an increase in h_{PO} induces a change in h_{max} and VI due to changes in \bar{F}_{net} and t_{PO} which we assumed would be related by a negative linear relationship.

Our results confirmed our first hypothesis and verified that an increase in h_{PO} induced a change in h_{max} and relative VI which was illustrated by almost perfect quadratic relationships between these parameters. These results align with previous studies reporting a quadratic relationship between h_{max} - and relative VI - h_{PO} (Gheller et al., 2015; Kirby et al., 2011; Mandic et al., 2015; McBride et al., 2010; Mitchell et al., 2017; Salles et al., 2011). As expected, considering the mathematical relationship between relative VI and h_{max} , h_{PO} values that maximize relative VI were quite similar to those obtained from the relation between h_{PO} and h_{max} (71 ± 17 % vs 75 ± 21 %, respectively).

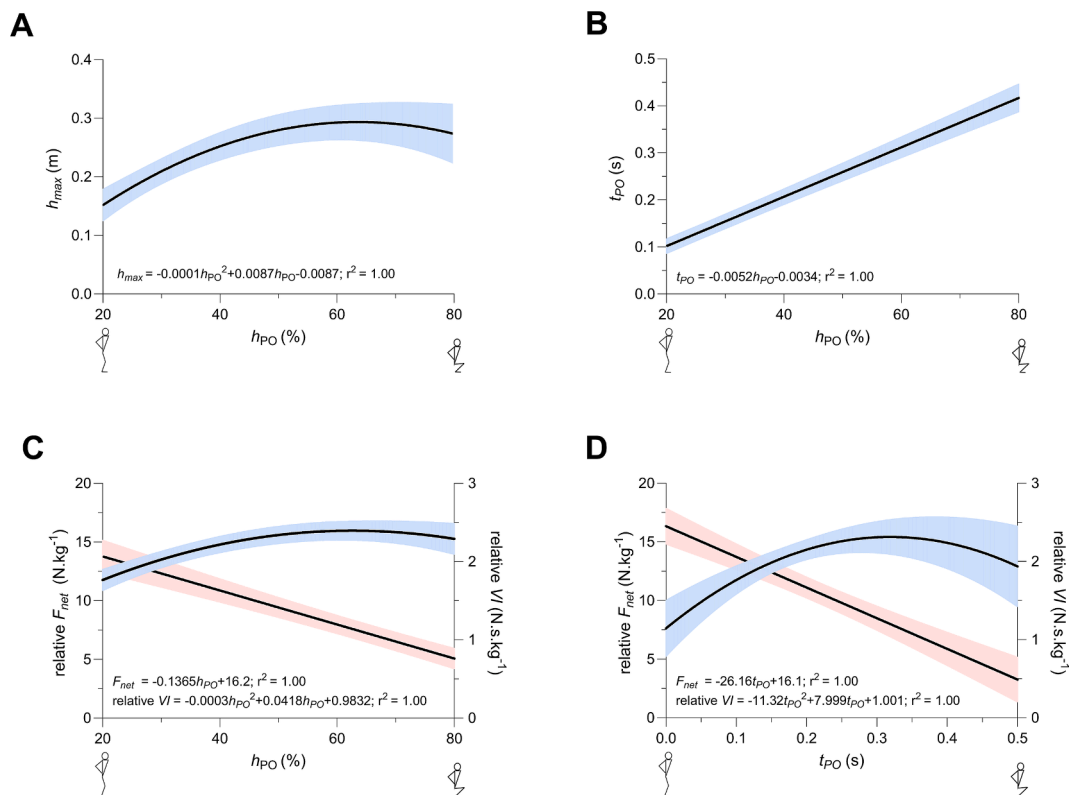


Fig. 2. Illustration of regressions performed on averaged data between h_{PO} or t_{PO} and the mechanical parameters. Black lines: mean regressions performed on averaged data. Blue and pink areas: 95 % confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article)

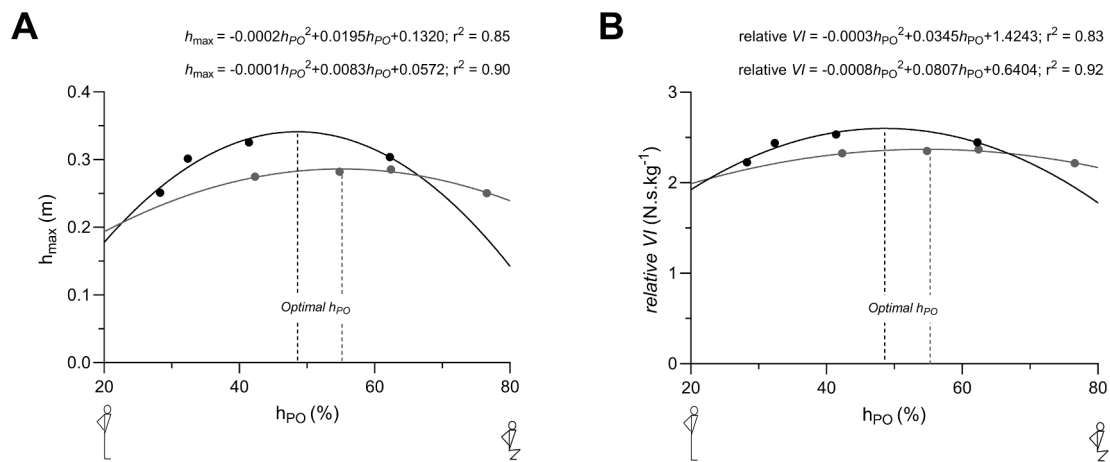


Fig. 3. Illustration of h_{max} - h_{PO} distance (Panel A) and relative VI- h_{PO} (Panel B) quadratic relationships of two typical participants. Black and gray dots represent h_{max} values obtained from four h_{PO} for participant 1 and 2, respectively. Black and gray dashed vertical lines indicate the individual optimal h_{PO} . h_{max} - and relative VI- h_{PO} quadratic relationships indicates similar individual optimal h_{PO} values of 48 % and 55 % associated with knee angles of 96° and 76° for participant 1 and 2, respectively.

However, some studies have shown an increased or unchanged h_{max} when increasing h_{PO} (Gheller et al., 2015; Kirby et al., 2011; McBride et al., 2010; Mitchell et al., 2017; Pérez-Castilla et al., 2021; Petronijevic et al., 2018; Sánchez-Sixto et al., 2018). These discrepancies might be attributed to differences in the experimental range of h_{PO} . Previous studies may have only recorded the ascending part of the quadratic relationship because the squats performed during testing were not deep enough. An underlying implication of the observed h_{PO} - h_{max} quadratic relation is evidence that an optimal h_{PO} that maximizes vertical jump performance exists and is associated with a high interindividual variability. Optimal h_{PO} , corresponding to the vertex of the relationship, has been previously defined by Mandic et al. (2015). In our study, three participants presented individual optimal h_{PO} values close to or higher than their maximal squat depth. This reflects their ability to limit the decrease of performance when h_{PO} increases, preventing them to reach the vertex of the quadratic regression in their working range of motion. However, 9 participants presented individual optimal h_{PO} values outside of their experimental range. Although quadratic fitting appears to be a good representation of the h_{max} - and relative VI- h_{PO} relationships over the experimental data range, extrapolated values out of the experimental range should be interpreted with caution. Expressed in meters, the individual optimal h_{PO} values of our participants were higher than those reported by Mandic et al. (2015) (0.57 vs 0.41 m, respectively). These differences in optimal h_{PO} values can be explained by the differences in populations, (CrossFit athletes vs basketball players) and individual characteristics as body geometry, prior experience with CMJ, training background or intersegmental coordination patterns. In addition, basketball is associated with time constraints requiring players to minimize their h_{PO} during jumping actions (Amasay and Suprak, 2022). Basketball players are trained to jump with shorter h_{PO} compared to CrossFit athletes who regularly perform explosive and loaded vertical jumps from a significant countermovement depth. Moreover, the mean knee angle corresponding to optimal h_{PO} was 100°, which is close to the mean self-preferred and recommended knee angles to perform CMJ maximizing h_{max} (Petronijevic et al., 2018). However, the large range of individual optimal h_{PO} observed in our study (optimal h_{PO} : 49–125 %, associated knee angles: 76–144°) could bring into question the choice of a standardized countermovement depth to compare individuals in their maximal vertical jump ability. Mandic et al., 2015 reported that allowing participants to jump with a self-preferred h_{PO} led to a 9 cm mean deviation from their optimal h_{PO} . These authors also showed that this difference in h_{PO} did not necessarily result in a significant difference in h_{max} because the self-preferred h_{PO} was close to the plateau of the h_{PO} - h_{max} quadratic relationship. In our study, a similar deviation of 9 cm

(11.9 ± 1.5 % of h_{PO}) from optimal h_{PO} led to a mean decrease of 0.6 ± 2.0 cm in h_{max} . Consequently, to compare individual maximal vertical jump abilities, we can suggest to use the preferred jumping depth as a reference condition or to determine beforehand the individual optimal h_{PO} from the h_{PO} - h_{max} relationship to better control the jumping test conditions.

To better understand the underlying mechanisms of the relationship between h_{PO} and relative VI, we focused on the influence of h_{PO} on the subcomponents of the mechanical impulse: \bar{F}_{net} and t_{PO} . We validated our hypothesis that a change in VI when h_{PO} varied was due to a concomitant decrease in \bar{F}_{net} and an increase in t_{PO} . Our regression analyses showed an almost perfect positive linear relationship between h_{PO} and t_{PO} , and a negative linear relationship between h_{PO} and \bar{F}_{net} . During a maximal jump, the correlation between h_{PO} and t_{PO} is due to the fact that the greater the vertical distance to achieve during push-off, the longer the time to push-off (Domire and Challis, 2007). The negative linear relationship between h_{PO} and \bar{F}_{net} is consistent with a previous study that also found a decrease in \bar{F}_{net} when h_{PO} increases (Sánchez-Sixto et al., 2018). The decrease in \bar{F}_{net} can mainly be explained by the torque-velocity-angle relationships of the joints involved in vertical jumping that depends on muscular force-length relationships, muscle-specific moment arms and neuromuscular activation capacities (Babault et al., 2003; Hahn et al., 2014). An increase in h_{PO} induces changes in joint angles and velocities, modifying joint torque production and so \bar{F}_{net} (Gheller et al., 2015; Kirby et al., 2011; Mandic et al., 2015; McBride et al., 2010; Mitchell et al., 2017; Salles et al., 2011). Considering vertical jumping, this could generate a specific force-velocity-position relationship applied to the CM explaining the changes in vertical force and velocity according to CM position. Indeed, Fig. 1 shows that an increase in h_{PO} (i.e., joint angles) induces a modification of the CM vertical velocity curve. As illustrated, jumping with different h_{PO} modifies the CM vertical velocity reached at a given knee angle (45° in Fig. 1), inducing changes in force production probably due to the CM force-velocity-position relationship. The vertical force-CM vertical position curve of the highest h_{PO} condition exhibits a typical shape. At the start of the push-off phase, the vertical force begins to decrease as position increases. This could be explained by the respective influence of velocity and position on force production due to the CM force-velocity-position relationship. The influence of h_{PO} on force and CM vertical velocity results in different v_{TO} values and so, different h_{max} . In addition, the countermovement depth associated with h_{PO} condition allows subject to reach different vertical force level at the start of push-off. A higher vertical force at the start of push-off was previously associated with

higher h_{\max} (Bobbert et al., 1996). Furthermore, other authors observed that a higher mean force production could be reached when h_{pO} decreases, but did not necessarily result in increased performance because of a reduced t_{pO} (McBride et al., 2010; Salles et al., 2011). In line with our first hypothesis, our results confirmed that there is a concomitant decrease in \bar{F}_{net} and increase in t_{pO} when h_{pO} increases, affecting the relative VI generation, and then h_{\max} . Our second hypothesis is confirmed as we reported an almost perfect negative linear relationship between \bar{F}_{net} and t_{pO} . Our findings show that vertical jump performance determined by the generation of relative VI appears as a compromise between force production capacity and available time for force application, both influenced by the distance of push-off.

Our study is the first to describe the relationship between \bar{F}_{net} and t_{pO} . The negative linear relationship between \bar{F}_{net} and t_{pO} suggests the existence of an individual $\bar{F}_{net-t_{pO}}$ profile describing the ability of an individual to maintain a high level of \bar{F}_{net} despite the increase in h_{pO} and t_{pO} . This individual $\bar{F}_{net-t_{pO}}$ profile certainly also reflects the individual characteristics such as prior experience with vertical jump, strength and conditioning background, range of motion, body geometry or intersegmental coordination. The individual relationship between \bar{F}_{net} and t_{pO} determines the capacity to generate mechanical impulse. Being that relative VI is the product of \bar{F}_{net} and t_{pO} , a negative linear relationship between \bar{F}_{net} and t_{pO} results mathematically in a quadratic relationship between relative VI and t_{pO} . The existence of a very large to almost perfect relative $VI-t_{pO}$ quadratic relationship was confirmed by our study. Since a negative linear relationship between \bar{F}_{net} and t_{pO} was observed, maximal relative VI (VI_{\max}) corresponds to an optimal \bar{F}_{net} ($\bar{F}_{net\ opt}$) and an optimal t_{pO} ($t_{pO\ opt}$). The relationship between \bar{F}_{net} and t_{pO} emerges as a novel indicator of vertical jump performance capacity, taking into account the influence of h_{pO} on force production. This finding could support the idea that performing resistance training at specific squat depth positions could induce changes in the slope of the $\bar{F}_{net-t_{pO}}$ relationship. These improvements would result in an increase in VI_{\max} , and a change in $t_{pO\ opt}$, modifying h_{\max} and h_{pO} at which it is reached.

While the results of this study are promising, limitations were noted. This study focused on a range of h_{pO} extending from $26.1 \pm 2.8\%$ to $76.5 \pm 4.3\%$ of the maximal countermovement depth and predicted optimal h_{pO} values outside the experimental range for 9 participants. Future studies characterizing the individual \bar{F}_{net} - and relative $VI-t_{pO}$ relationships over a wider range of h_{pO} are needed to predict more accurately individual optimal h_{pO} values. Additionally, our study described the individual \bar{F}_{net} - and relative $VI-t_{pO}$ profile based on experimental data collected from a population of CrossFit athletes. Future studies should investigate whether the \bar{F}_{net} - and relative $VI-t_{pO}$ relationships are sport-specific and if an optimal profile optimizing sport performance exists. Finally, future studies should explore the sensitivity of the \bar{F}_{net} - and relative $VI-t_{pO}$ relationships to resistance training at various depths, and how these adaptations influence vertical jump performance.

5. Conclusion

This study confirmed the influence of distance of push-off (h_{pO}) on relative vertical impulse (VI) and on vertical jump performance (h_{\max}). The apex of the quadratic relationship between h_{pO} and VI or h_{\max} indicates an optimal h_{pO} maximizing performance. These results highlight the importance of considering the individual optimal h_{pO} from the $h_{pO}-h_{\max}$ relationship or, at the very least, the preferred h_{pO} when assessing vertical jump performance. The existence of a negative linear relationship between mean net vertical external force (\bar{F}_{net}) and push-off time (t_{pO}) emphasizes the existence of an individual \bar{F}_{net} - and relative $VI-t_{pO}$ profile appearing as a novel indicator of vertical jump performance. This provides new insights to characterize vertical jump mechanical parameters and ways to optimize training and jump performance.

CRedit authorship contribution statement

Félicie Pommerell: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Boyas Sébastien:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Pierre Samozino:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Conceptualization. **Baptiste Morel:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Conceptualization. **Begue Jérémie:** Writing – review & editing, Visualization, Validation, Resources, Methodology. **Abderrahmane Rahmani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nicolas Peyrot:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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