Journal of Strength and Conditioning Research Publish Ahead of Print
DOI: 10.1519/JSC.0000000000000502

Title page

Title of the Article

Kinetic and kinematic analysis for assessing the differences in counter-movement jump performance in Rugby players

Running Head

Ground Reaction Forces in vertical jump

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Funding: No grant or external financial support was provided for this project

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ABSTRACT

The aim of this study was to ascertain the differences in kinetic and kinematic profiles between better and poorer performers of the vertical jump within a homogeneous group of trained adults. Fifty rugby players were divided into low scoring (LOW) and high scoring (HIGH) groups based on their performance in the vertical jump. The force, velocity, displacement, and RFD-time curves were analyzed in order to determine the differences between groups. The analysis of the data showed differences in all the patterns of the ensemble mean curves of the HIGH and LOW groups. During the eccentric phase, the differences in the HIGH group with respect to the LOW group were: Lower crouch position, higher downward velocity, and higher force and rate of force development during the braking of the downward movement. During the concentric phase, the HIGH group achieved higher upward velocity, higher force at the end of phase, and a higher position at take-off. The higher jump performances appear to be related to a more effective stretch-shortening cycle function which is characterized by a deeper and faster counter-movement with higher eccentric forces being applied to decelerate the downward movement leading to enhanced force generation during the concentric phase.

Abstract Word Count: 198

Keywords: Stretch shortening cycle, force, velocity, displacement, rate of force development

INTRODUCTION

The vertical jump can be considered a valid and reliable tool for assessing leg power in many sports which is used extensively in monitoring performance by coaches and strength and conditioning professionals (2). Contact mats are frequently used to assess the vertical jump performance and monitor training responses (12). While these may be useful in monitoring overall performance and providing estimates of effective use of stretch-shortening cycle, the data obtained from force plate analysis are more informative. The force platform records the ground reaction forces during the vertical jump and provides information on the athlete's force production and rate of force development. Analysis of these data can improve our understanding of the underlying qualities that contribute to the performance (16). From ground reaction force-time data, the velocity and displacement of the center of mass with respect to time can be calculated using the impulse-momentum theorem (20). The net force is integrated with respect to time to calculate the velocity and this can be used together with the equations of motion to determine the displacement of the center of mass throughout the jumping movement (20). It is possible to distinguish between athletes with low or high jumping ability by evaluation of force, velocity and displacement during vertical jump (8, 21, 32) or to examine training effects (8, 9). Several studies have analyzed the forces generated during the vertical jump and their relationship to performance (8-10, 13, 18, 25). Athletes proficient in jumping, demonstrate higher peak and average forces in comparison to less proficient jumpers (8, 10). Similarly, higher jumpers achieve greater peak velocities (8, 9, 13) and greater displacement of the center of mass (19, 31). These studies, although important in understanding the differences in biomechanical aspects of the vertical jump among various athletes of different levels, do not provide data describing the manner in which the best jumpers applied force.

Examination of the literature shows that most of the previous studies have used discrete variables such as peak force or average force to describe performance in the vertical jump. While this type of analysis is useful, it may not be sufficient to fully explain performance or training adaptations. A single discrete measure of a continuous variable where large amounts of data are discarded can result in the loss of relevant information (26). The analysis of continuous biomechanical variables based on time series data could improve understanding of how the force is generated during the execution of movement (26). Despite the utility of this methodology, only a few studies have analyzed the variations in the patterns of the force-, velocity-, and displacement-time curves to assess jumping performance (7-9). These studies observed differences in the patterns of the curves and concluded that curve analysis offers a simple, yet powerful monitoring technique that can be used to improve the understanding of the biomechanical aspects of the vertical jump. This type of analysis can help coaches and athletes to identify the specific movement phases where differences occur and redirect the emphasis of training, leading to improved performance in the vertical jump. These differences in the patterns of the force-, velocity-, and displacement-time curves can be used to ensure more effective use of stretch-shortening cycle function during the performance of vertical jump.

In sports training, small differences between athletes of similar performance level can decide success or failure in sport. Many studies that analyze the force generated in the vertical jump focus on comparing dissimilar and heterogeneous groups, such as jumpers and non-jumpers (8, 31), however, the results from a heterogeneous sample can be misleading if attempting to generalize those results to a homogeneous sample. In order to optimize the training process, it is important that coaches and athletes know the specific factors which determine jumping performance within the athletic population. Based on the literature, there are only a few studies that have ascertained differences in jumping biomechanics between groups of athletes within the same sport (29, 32). Vanezis and Lees (32) observed that differences in vertical jump performance amongst soccer players were related to the ability of the best jumpers to produce greater muscle force and power while the coordination of the body segments played a less important role. Given the paucity of research which has analyzed the vertical jump within homogeneous groups, further studies are needed to advance the understanding of how force must be applied to improve jumping ability among athletes within a single-sport population.

Therefore, it is important to analyze the whole force-time curve during the performance of vertical jump in order to determine the biomechanical adaptations amongst athletes of similar performance levels. Consequently, the purpose of this study was to ascertain the biomechanical differences between better and poorer performers of the vertical jump within a homogeneous group of trained adults. Specifically, this study compared the force-, velocity-, displacement-, and rate of force development (RFD) -time curves between rugby players of similar training backgrounds with the intent of understanding how these four continuous variables may distinguish high and low level performers in the vertical jump and hence can be used to plan training progressions.

METHODS

Experimental Approach to the Problem

This was a cross-sectional, comparative study of high and low level performers of the vertical jump within group of rugby players. The groups were selected based on participants' maximum vertical jump height calculated from jump impulse (20) derived from the ground reaction force recorded via force plate. Comparison between groups was used to investigate differences in the biomechanical factors which determined jump performance. An independent sample t-test was used on a point by point basis to determine significant differences between both groups. The performance level (group) was the independent variable, while the force-, velocity-, displacement-, and RFD-time curves were the dependent variables. A continuous curve analysis of these biomechanical variables rather than discrete analysis was used to determine the differences in the kinetic and kinematic parameters between groups. This involved comparison of the normalized ensemble average curves for each group.

Subjects

Fifty (n = 50) elite athletes from a Spanish rugby team, ranging between 16 to 19 years of age were recruited for this study. No participants had any past history of nervous system or muscular dysfunction, except for a few cases of typical impact injuries which had completely recovered at the time of measurements. The study had obtained ethical approval from the University Research Ethics Committee and all adult participants and parents/guardians of under-age participants signed informed consent forms before participating in the study.

Procedures

Participants were instructed to perform counter-movement jumps (CMJ) on a portable force platform (Quattro Jump®, Kistler Instrumente AG, Winterthur, Switzerland). Before each test, all participants performed 10 minutes of warm-up activity including a brief period of low-intensity aerobic exercise, some short duration dynamic stretching exercises and one set of 5 sub-maximal jumps. Since all participants were physically active and regularly performed activities including jumping, a short familiarization session was sufficient to ensure the participants could complete the jumping tasks to a satisfactory level. Vertical ground reaction force (Fz) data were sampled at 500 Hz and the duration of data collection period was 5 seconds. A force plate and proprietary computer software (QuattroJump, Type 2822A1-1, Version 1.0.9.2) was used to record the force values.

The instructions for each participant were standardized. They included a detailed verbal explanation and a physical demonstration by the experimenter. The importance of jumping as high as possible was emphasized. In performing the CMJ, the participants stood upright and stationary for at least 2 seconds during which body weight was recorded, then they jumped as high as possible. For all jumps, participants retained the "hands on hips" position until the landing phase. Three successful jumps were recorded for each participant, with at least 2 minutes of rest allowed between jumps. The jump with the greatest height was selected for analysis.

Analysis

The vertical component of center of mass velocity was estimated using the impulse method (20). Net impulse was obtained by integrating the net Fz force, from 2 s prior to the first movement of the participant (30), using the trapezoid method. Subsequently, the vertical velocity of the center of mass was calculated by dividing the net impulse by the participant's body mass. Vertical center of mass displacement throughout the ground contact period was derived by numerically integrating the vertical center of mass velocity. Finally, the RFD throughout the motion was calculated from first derivate of the vertical force with respect to time using a point-to-point moving average window of five data points. In order to exclude the influence of body size on the values computed, the variables quantifying force were normalized to body weight (BW) while the variables quantifying displacement were normalized to leg length (LL) where LL was defined as the difference between standing height and sitting height. The sitting height was measured with subjects seated with their backs pressed to the wall, on a stool placed directly under a height measuring rod.

Temporal phase analysis of the jumps was conducted as follows: The force-, velocity-, displacement-, and RFD-time curves from all participants were selected from the start of the movement to instant of take-off. The start of the movement was identified on the recommendations of Street et al. (30) by inspecting the force-time records to identify the first instant where Fz deviated above or below body weight (BW) by more than one threshold. The threshold was defined as 1.75 times the peak residual found in the 2 seconds of the BW averaging period. A backward search was then performed until Fz passed through BW. The instant of take-off was defined as the first intersection of Fz with an offset threshold where, the threshold was determined by adding the average flight time (i.e., 0.4 seconds) and the peak residual to the offset (30).

Group Analysis

In order to evaluate the biomechanical differences between groups with different levels of performance, the participants were categorized into tertiles based on the participants' maximum jump height. The highest tertile was defined as the high scoring (HIGH) group (n = 17, age 17.8 ± 1.2 years, height 1.75 ± 0.07 m, mass 73.9 ± 11.0 kg, height jump 0.57 ± 0.03 LL) and the lowest tertile was the low scoring (LOW) group (n = 17, age 17.5 ± 0.9 years, height 1.77 ± 0.04 m, mass 87.4 ± 18.6 kg, height jump 0.42 ± 0.04 LL). The middle tertile was rejected for the rest of the analysis, so the final sample selected to study was thirty-four subjects (n = 34).

To compare the curves between the LOW and HIGH groups, the dataset of each parameter was normalized to 500 points using a piecewise linear length normalization procedure (14).

This technique expands or compresses the time axis in order to find temporal alignment at points of interest (27). Three points of interest were identified which defined two sub-phases of the jump. The eccentric phase was defined from start of the movement to the lowest crouch position and the concentric phase was from lowest crouch position to instant to take-off. This allowed all force-, velocity-, displacement-, and RFD-time curves to be expressed over normalized periods of percentage time, such that individual data could be aligned to identifiable events. Each normalized trace was averaged over all participants to provide a mean curve for each variable and each group.

Statistical Analyses

Statistical analyses were performed to evaluate the differences between HIGH and LOW groups using PASW (SPSS, Inc., Chicago, IL). Normality of the data sets was verified using the Shapiro-Wilk test. If the data were normally distributed within groups, an independent samples Student t-test was applied at each time point throughout the movement to determine differences in the force-, velocity-, displacement-, and RFD-time curves between LOW and HIGH groups. If the data were not normally distributed, then a Mann-Whitney U-test was used. Statistical analysis was completed by the estimation of the effect size (ES) using Cohen's dz (6) to evaluate the magnitude of differences between groups. For all statistical procedures, an alpha level of $P < 0.05$ was used to establish significance and the criteria for interpreting the ES were: trivial = 0.00 – 0.19, small = 0.20 – 0.59, moderate = 0.60 – 1.20 and large >1.20 (15).

RESULTS

The results showed that there were significant differences between the HIGH and LOW groups in all the patterns of the ensemble mean curves (figures 1-4). The greatest number of differences occurred in the velocity-time and displacement-time curves. In the velocity-time curve, the significant differences between the HIGH and LOW groups were distributed across both eccentric and concentric phases (Figure 2). The differences in the eccentric phase occurred from 48.4% to 71.0% of normalized time, where the downward velocity of the HIGH group was greater than the LOW group ($t \leq -2.052$, $P \leq .049$, ES ≤ -0.7). In almost all of the concentric phase (from 72% to 100% of normalized time), there were differences between the groups and the HIGH group generated higher velocity from the beginning of the upward movement ($t \geq 2.196$, $P \leq .037$, ES ≥ 0.8). Similarly, there were differences between the two groups throughout 44.8% of the normalized time in the displacement-time curve (Figure 3). These differences were observed both in crouch position (from 50.4% to 93.8% of normalized time) and in take-off (from 98.6% to 100% of normalized time). The results showed that the HIGH group displaced their center of mass further in the crouch position ($t \leq -2.063$, $P \leq .049$, ES ≥ -0.7) and elevated their center of mass higher, adopting a more upright posture at take-off ($t \geq 2.144$, $P \leq .040$, ES ≥ 0.8) compared with the LOW group. Significant differences were found between groups in the force-time curve at two separate time intervals (Figure 1). The first of these occurred during the last moments of the eccentric phase, from 67.2% to 71.4% of normalized time. In this interval, the force values were higher in the HIGH group than in the LOW group ($t \geq 2.047$, $P \leq .049$, ES ≥ 0.7). The second interval was at the end the concentric phase, from 89.6% to 99.2% of normalized time and the force values were higher in the HIGH group compared to the LOW group ($t \geq 2.064$, $P \leq .050$, ES ≥ 0.7). In the RFD-time curves, the only interval with significant differences was in during the eccentric phase, from 63.4% to 65.2% of normalized time and this coincided with the maximal RFD values (Figure 4). During this interval the RFD values were higher in the HIGH group than in the LOW group ($t \geq 2.077$, $P \leq .046$, ES ≥ 0.7).

DISCUSSION

Vertical jump performance is related to the ability to produce mechanical work (4) therefore a higher jump height can be attributed to an enhancement of the work done on the center of mass (20). The mechanical work depends on the force applied and the distance over which the force is applied. Both the force-time and the displacement-time curves showed significant differences between the HIGH and LOW groups during the eccentric and concentric phases of the movement. During the final instants of the eccentric phase, the HIGH group displaced their center of mass lower and applied higher force to decelerate the downward movement. The positive effect of increasing both the depth of the counter-movement and the eccentric load on improving the jump performance has been reported previously (3, 24). The HIGH group maintained a deeper position than the LOW group during most of the movement, with a maximum difference of 28.8% between HIGH and LOW groups at the lowest crouch position. This deeper crouch enabled the HIGH group to increase the vertical distance travelled by the center of mass during the concentric phase. Previous studies have shown that performance may be enhanced by increasing the distance over which force can be generated (4, 18, 22, 24, 31). An increase in the range of motion, through which the force is generated, can increase the net impulse and consequently enhance the take-off velocity (20). This performance improvement can only be achieved if the applied force levels are maintained throughout the concentric phase. Previous studies (18, 28) reported that in deeper crouch positions, the tension in the joints increases, resulting in decreased capacity to generate force, however, the results of this study show that the HIGH group achieved higher forces than the LOW group at the end of the eccentric phase in spite of adopting a deeper position. Previous studies have found that increases in the magnitude of the eccentric load in stretch-shortening cycle activities can improve the jump height (24), since it facilitates the subsequent generation of higher concentric force and ultimately increases the vertical take-off velocity (4, 8, 9, 17). The higher force produced at the end of eccentric phase increases the ability to develop force rapidly during the counter-movement. The HIGH group achieved higher RFD levels than the LOW group during the braking phase of the downward movement. Moreover these differences coincided with the instant that peak RFD values were achieved. These results are in general agreement with McLellan et al. (23) who reported a significant correlation between peak RFD and vertical jump performance. This outcome may support the use of RFD during the eccentric phase as a parameter that differentiates between better and poorer performers of the vertical jump within a homogeneous group of trained adults. Similarly, in the displacement- and RFD-time curves, significant differences were observed during the eccentric phase and also in the patterns of the velocity-time curves between the two groups. The HIGH group generated higher download velocity than the LOW group, with the mean peak downward velocity being 19.3% higher in the HIGH group. Several previous studies have linked an increase in downward velocity with an increase in jump performance (1, 8, 9, 13), concluding that the peak eccentric velocity can be both a good predictor of performance and an indicator of the effectiveness of training. In addition, the results showed significant differences in all variables analyzed between the two groups during the eccentric phase and these differences were consistent with the concept that maximum jump performance is dependent on effective utilization of the eccentric phase.

During the concentric phase, the force-time and displacement-time curves were significantly different which suggests that the HIGH group produced greater mechanical work. In the displacement-time curve, differences were observed at the beginning and end of the concentric phase. The differences at beginning were a consequence of a deeper crouch during the counter-movement, while differences at the end of the concentric phase suggest that the

HIGH group adopted a more upright posture at take-off. This difference in posture could be due to incomplete extension of the lower limbs in the LOW group during the upward movement which indicates that the LOW group participants had insufficient strength in final knee extension or ankle plantarflexion. Moreover, during the latter part of the upward movement the force applied by the HIGH group was higher than in the LOW group thereby reinforcing the rationale of muscle weakness. This greater strength of the HIGH group could also result in increased displacement their center of mass in the crouch position. In a previous study, Bobbert et al. (5) observed that when the crouch position was deeper, the activation onset of the plantarflexors was delayed. This provides better timing in the activation of the extensor muscles of the lower extremity in proximo-distal sequence which allows the athlete to achieve a take-off position where the joints are extended as far as possible. While significant differences in the force values were observed only during the latter part of the upward movement, the velocity of the HIGH group was higher than the LOW group throughout most of the concentric phase. This discrepancy can be explained by the fact that force-time integration produces a cumulative effect on impulse and consequently, the velocity of the mass center. During the first moments of the concentric phase, the differences in force between the HIGH and LOW groups were not significant but there was a moderate group-related effect size. Since velocity is obtained from the integral of force with respect to time, the moderate force differences between the groups accumulated over time and caused large differences in the velocity between groups. The results showed that the higher velocity of the HIGH group during the concentric phase was not achieved by a greater ability to develop force rapidly. There were no significant differences in RFD between the two groups during the concentric phase suggesting that this parameter did not seem to directly influence on jumping performance. This finding was consistent with the results of Cormie et al. (8) who showed no significant differences in concentric RFD between groups with different levels of performance.

This study included rugby players of the same competitive level and training frequency however the body composition of the players was not tested. Ferreira et al. (11) showed that anthropometric characteristics can affect jumping performance and observed an inverse relationship between the percentage of body fat and jumping performance. Although the current study normalized the force to body weight, the potential influence of percentage body fat on the vertical jump performance in this study remains unknown.

This study demonstrated the important role of the counter-movement as a contributor to the differences in jumping performance within homogeneous group of athletes. Significant differences between HIGH and LOW groups were observed in the patterns of the all the curves examined. The higher jump performances appear to be related to a more effective stretch-shortening cycle function which is characterized by a deeper and faster counter-movement with higher eccentric forces being applied to decelerate the downward movement leading to enhanced effectiveness of force generation during the concentric phase. Future studies should determine how the patterns of force-, velocity-, displacement- and RFD-time curves are modified with different types of training and how these patterns are associated with field-based tests for assessing performance.

PRACTICAL APPLICATIONS

The results of this study may help strength and conditioning professionals in two ways: presenting the usefulness of the analysis of continuous variables in evaluating performance and assisting in selecting exercises more appropriate to improve jumping performance. The procedures which assess continuous variables can provide a valid method to determine which patterns of force-, velocity-, displacement-, and RFD-time curves provide better performance in the vertical jump. This method clearly identifies temporal phases of movement where differences are produced leading to improved understanding of the biomechanical aspects of the vertical jump. These phases coincided with the instants of deceleration and the instants prior to take-off where the athlete adopted a more upright position. This research helps coaches and athletes to determine the specific adaptations which improve performance in the vertical jump within a homogeneous group of athletes. The differences in the jump performance were a consequence of increased range of motion of counter-movement and the generation of higher ground reaction forces at the end of eccentric and concentric phases. This suggests that the use the specific strength training on lower limbs focused to increase the range of motion through which the athlete is able to generate forces could improve the vertical jump performance. Finally, this research suggests that the ability to generate high forces to decelerate the downward movement seems to be an indicator of the effectiveness of the stretch-shortening cycle, therefore training which includes exercise with rapid eccentric-concentric transitions could improve performance in the vertical jump.

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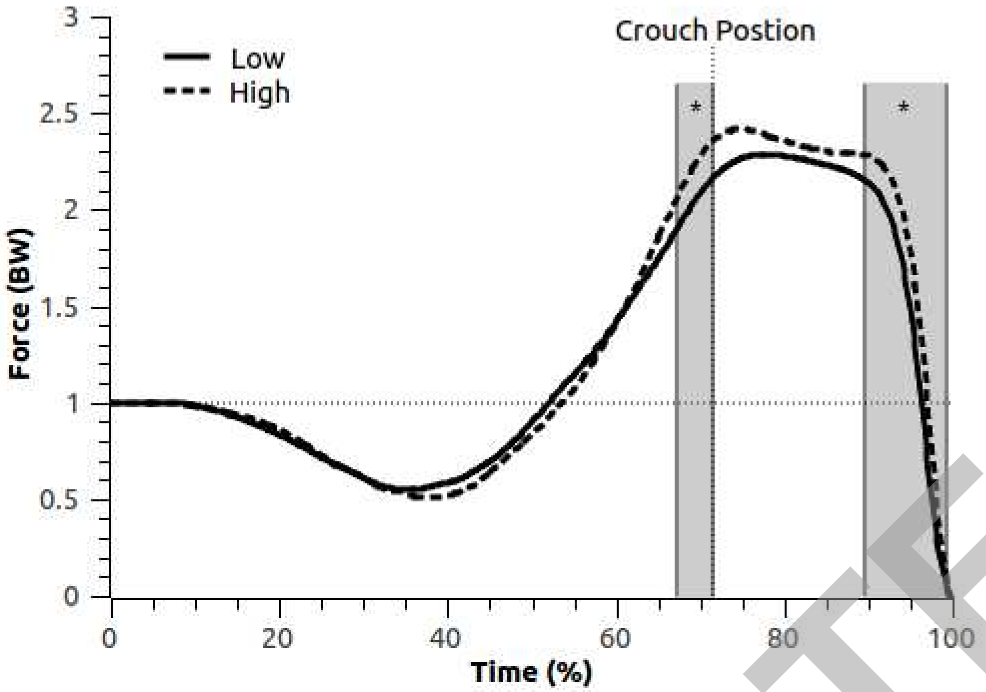
FIGURE LEGENDS

Figure 1. Comparison of the ensemble average force-time between HIGH and LOW groups. * Denotes statistically significant difference between groups ($P < .05$).

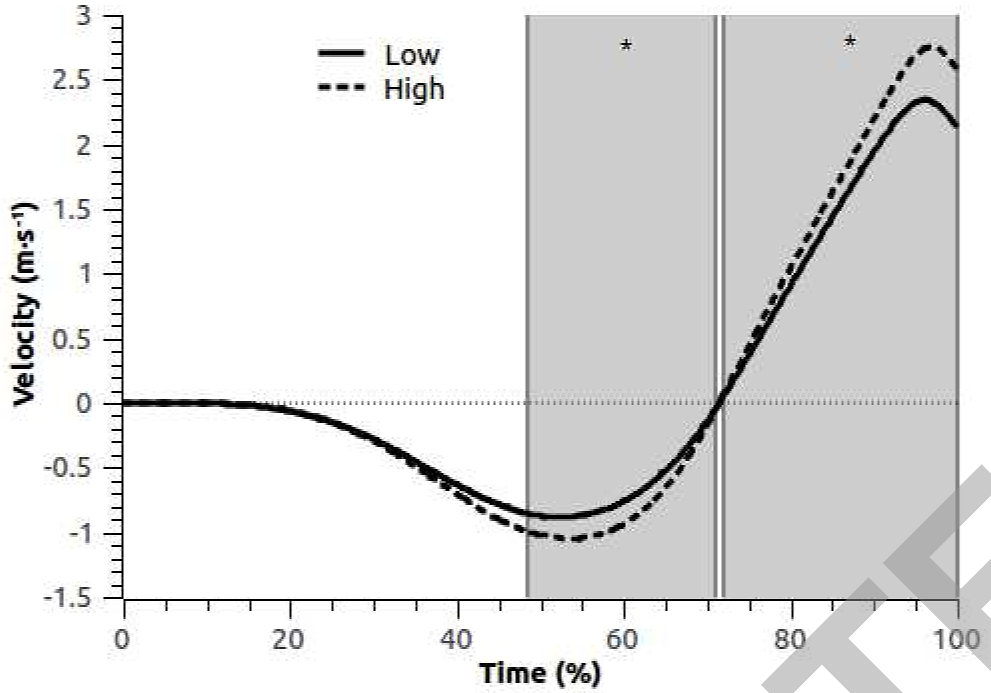
Figure 2. Comparison of the ensemble average velocity-time between HIGH and LOW groups. * Denotes statistically significant difference between groups ($P < .05$).

Figure 3. Comparison of the ensemble average displacement-time between HIGH and LOW groups. * Denotes statistically significant difference between groups ($P < .05$).

Figure 4. Comparison of the ensemble average rate of force development (RFD) with respect to time between HIGH and LOW groups. * Denotes statistically significant difference between groups ($P < .05$).



Crouch Postion
Low
High
*
*
Force (BW)
3
2.5
2
1.5
1
0.5
0
0
20
40
60
80
100
Time (%)


Low
High
Velocity (m·s⁻¹)
Time (%)
*
*
3
2.5
2
1.5
1
0.5
0
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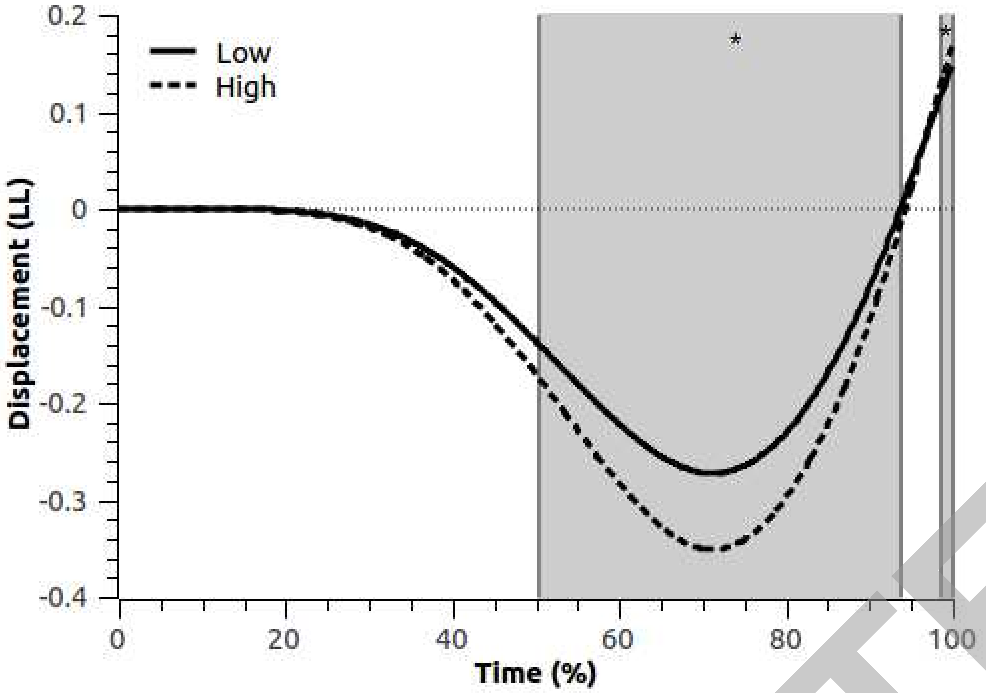
-1
-1.5
0
20
40
60
80
100


Low
High
Displacement (LL)
Time (%)
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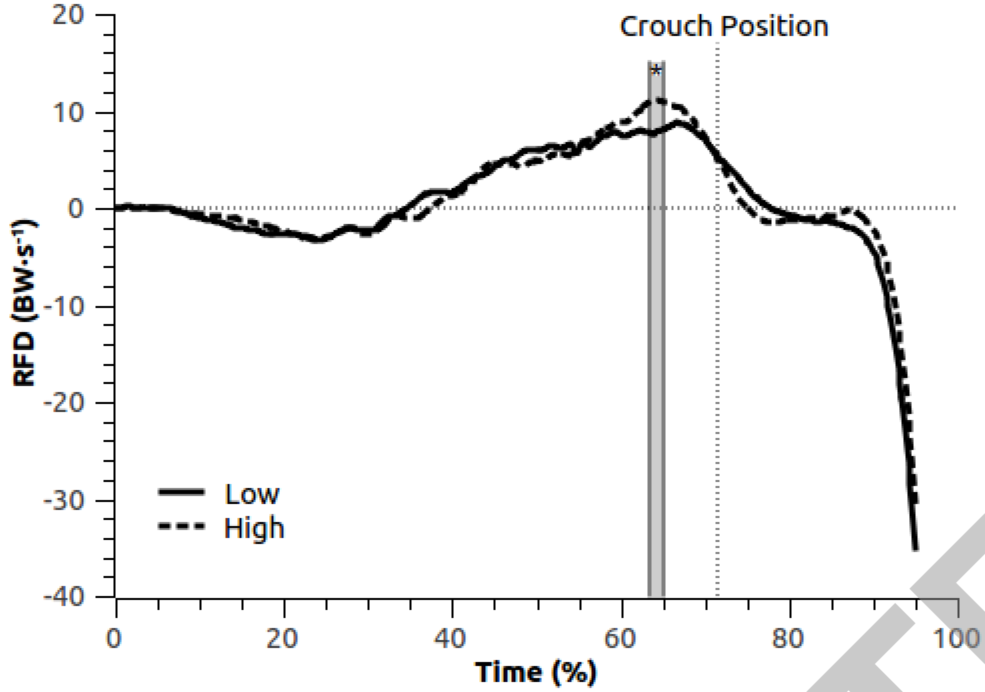
0
-0.1
-0.2
-0.3
-0.4
0
20
40
60
80
100
*
*


Crouch Position
*
RFD (BW·s-1)
Time (%)
Low
High
20
10
0
-10
-20
-30
-40
0
20
40
60
80
100