Vertical- vs. horizontal-oriented drop-jump training: chronic effects on explosive performances of elite handball players
ABSTRACT

This study aimed to assess the chronic effects of vertical and horizontal drop-jump-based protocols on neuromuscular explosive abilities such as jumping, sprinting, and change of direction (COD).

Eighteen elite male handball players (age 23.4 ± 4.6 years; height 192.5 ± 3.7 cm; weight 87.8 ± 7.4 kg) were assigned to either vertical drop jump (VDJ) or horizontal drop jump (HDJ) group training twice a week for 10 weeks. Participants performed 5-8 sets × 6-10 repetitions of vertical-alternate (VDJ) or horizontal-alternate (HDJ) one-leg drop-jumps, landing from the top of a platform 25 cm in height. Before and after training, several performance, kinetic and kinematic variables were assessed. The HDJ led to greater improvement of the sprint-time (-8.5% vs. -4%; \( p < 0.05 \)) and COD performance in comparison with the VDJ (-7.9% vs. -1.1%; \( p < 0.05 \)), while the VDJ caused greater improvement in the vertical jump compared with the HDJ (+8.6% vs. +4.1%; \( p < 0.05 \)). Moreover, the VDJ regimen compared with the HDJ, induced greater changes in the kinetic variables associated with vertical jumping performance, such as peak ground reaction forces (+10.3% vs. +4.3%), relative impulse (+12.4% vs. +5.7%), leg-spring stiffness (+17.6% vs. +4.6%), contact time (-10.1% vs. -1.5%), and reactive strength index (+7.2% vs. +2.1%); all comparisons with \( p < 0.05 \). Conversely, the HDJ regimen was able to improve the short-distance and COD performances by increasing the step length (+3.5% vs. +1.5% with \( p < 0.05 \)) and reducing the contact time on COD (-12.1% vs. -2.1% with \( p < 0.05 \)) more than the VDJ. This investigation showed the crucial role that specific plyometric regimens play in optimizing similar biomechanical featured functional performances such as jumping, sprinting and COD.

Key words: stiffness – plyometrics – neuromuscular abilities – sprint – agility – team sport
INTRODUCTION

Handball is a strenuous contact team sport that involves high-intensity short-duration activities such as sprinting, jumping, turning, pushing, blocking, and throwing (10). Previous investigations, focusing on the performance model of the discipline, have reported the game featured by a mean of 190 rhythm variations, 279 changes of direction, and 16 jumps, for a total of 485 high-intensity actions (8,9). High-intensity actions such as sprints, counter-attacks and changes of direction (COD), account for 10-13% (21,42) of the total distance covered in both junior and elite handball games. Moreover, it is important to consider that in goal situations, either the scoring player or the assisting one mostly performs actions with high-intensity technical demands (e.g., jumps, shots, duels), within a restricted space and with a very limited amount of time (21). In this regard, Sibila et al. (42), by using video match analyses, have demonstrated a mean 10- to 12-m sprint time of 2.3 seconds, and a mean of 50 turns including COD (180°) occurring per game (42). Hence, the intermittent and high-intensity profile nature of the handball play highlights the importance of neuromuscular and explosive capabilities of the player as key components for successful participation (9). Optimal initial acceleration (4), jumping, sprinting and the agility to change direction, start, and stop quickly over short distances (41) are all crucial elements of fast play and discriminating physical demands at top levels (4,21).

Plyometrics are exercises characterized by rapid stretch-shortening cycle (SSC) muscle actions including a range of unilateral and bilateral bounding, hopping and jumping variations (26). Typically, plyometric exercises are performed with little to no external resistance, such as with body mass only, and overload is applied by increasing the stretch rate through minimizing the duration of the SSC (i.e., countermovement, bounce, reactive jumps (28)) and/or stretch load by increasing the height of the drop during drop jumps modes (12). Plyometric exercises can therefore be tailored to train either short SSC movements characterized by a 100-250 ms duration (1,40) (i.e., ground contact in sprinting), or long SSG movements characterized by duration greater than 250 ms (1,40) (countermovement jumps or COD). Considering this biomechanical scenario, the ability to target
both short and long SSCs, as well as the ballistic nature of plyometrics, highlight these conditioning exercises as very specific for a wide variety of movements typically encountered in sport. Therefore, it is not surprising that scientific studies generally report this training regimen to be an effective means for improving explosive neuromuscular impulse-dependent components such as acceleration, jumping, sprinting, and change of direction (COD) ability (5,26,35,36). A recent body of research has addressed its attention to clarifying and profiling the specific effects of applying vertical or horizontal unloaded plyometric jumps on neuromuscular capacities of elite athletes (35). Contextually, Loturco et al. (24) compared the short-term training effects of vertically- and horizontally-oriented exercises on neuromuscular performance in young soccer players. The authors reported on the capacity of plyometrics to transfer specific neuromuscular gains to the acceleration, speed, and jumping abilities of soccer players. More recently, Dello Iacono et al. (10), assessing the acute effects of vertical and horizontal drop-jump-based post activation potentiation (PAP) protocols on neuromuscular tasks in elite handball players, confirmed that horizontal jumps are more targeted to acutely increase acceleration over short distances and COD ability, whereas vertically-oriented plyometrics should be directed to vertical jump performance. From a methodological perspective, in order to enhance athletic performance in highly-trained athletes, it is almost obligatory to stress the athletic quality of interest through motor schemes and biomechanical patterns similar to the addressed ability, thus inducing short-term responses and long-term adaptations (38). Profiling the possible transference effects from specific plyometrics to horizontally- or vertically-oriented explosive, could provide coaches with a commonsense approach for strategically selecting exercises in the athlete’s overall training program.

Therefore, the objective of this study was to investigate the effects of two drop-jump-based protocols on neuromuscular abilities manifested in jumping, sprinting, and COD skills, in elite handball players. Due to the major importance of horizontal force production capability in enhancing sprinting performance over short distances, and the predominant participation of vertical forces on
vertical jump tasks, it is expected that implementation of horizontal or vertical plyometrics would induce specific mechanical adaptations related to the axis of the movement.

**MATERIAL AND METHODS**

*Experimental Approach to the Problem*

This study adopted a counterbalanced, fully controlled research design with randomized allocation of training intervention and pre-post assessments. Accordingly, participants were divided into two training groups that performed either VDJ \((n=9)\) or HDJ \((n=9)\) in addition to their normal handball training sessions. We acknowledge that the present study design could have been more powerful with a nonintervention control group. However, the population from which well-trained handball players can be drawn, belonging to the same team and with a common conditioning background, is limited, and therefore this dictated the approach we utilized. The two training interventions were based on a very recent investigation of Dello Iacono et al. (10), reporting acute biomechanical adaptations associated with the vertically- and horizontally-oriented drop-jump tasks and specific transference effects in enhancing consequent performance outcomes. The current study was conducted during the mid-part of the handball in-season period (November 2015 - January, 2016). Overall, the study lasted 12 weeks and consisted of one week of pre-testing, ten weeks of specific training (twice a week), and one week of post-testing. To isolate the effect of the two training protocols, the additional fitness training sessions (e.g., technical, tactical, and strength) during the ten weeks of training were identical for both groups and were limited to specific handball training exclusively. Tests included a countermovement jump (CMJ) and the 25-m (12.5-m + 12.5-m and 180° COD) shuttle sprint whose performance, kinetic and kinematic variables were assessed at pre- and post-intervention points.

*Subjects*
Based on the assumption that between-group differences in agility performance time (8) of 0.08±0.03sec and in jump performance (11) of 1.7±0.3cm are meaningful, we used G*Power Software to determine that a sample size of ≥ 7 participants per group would provide maximal chances of 0.5 and 25% of type I and type II errors, respectively. Eighteen elite male handball players (age 23.4 ± 4.6 years; height 192.5 ± 3.7 cm; weight 87.8 ± 7.4 kg), were recruited to participate in the study. Players had at least eight years of high-level practice and six years of specific jumping and sprinting training experience. They trained with their own club once a day for 90 min, five days per week, undergoing technical, tactical, and strength training. Strength training consisted of ~2-h a week of “resistance exercises” for upper limb muscles only. Pilot studies conducted prior to the present study showed that technical and tactical training sessions can be qualified as intermittent and moderate-intensity exercise (45-75% maximal oxygen uptake performed over 1-1.5 h). In order to be included in the study, players had to have participated in at least 90% of the training sessions in the two previous competitive seasons. Written informed consent was obtained from the participants after receiving an oral explanation of the purpose, benefits, and potential risks of participating in the study. This study was approved by the Institution's Ethics Committee.

**Procedures**

One week before the **beginning of the training schedule**, the participants performed a familiarization session to become acquainted with the protocols and testing procedures. On the same day anthropometric measurements of height and body mass (SECA model 284, Germany) were taken. Following the familiarization session and **prior to the training intervention, the athletes reported to the sports hall on two separate occasions, two days apart, with the aim of assessing the test-retest reliability of the measurements.** Finally, the **same battery of tests was conducted after the 10-week training period.** All tests were performed in the same regular indoor court, and all participants wore suitable running shoes to limit possible variability within the testing procedure. Each subject completed all trials at the same time of the day (12:00 p.m. - 02:00 p.m.), and in similar
ambient conditions of temperature (21.2±0.5°C) and relative humidity (61±2.5%). These conditions maintain test validity and reliability with regards to any influence of circadian rhythms and diurnal variation (14). In order to prevent an unnecessary fatigue effect, players and coaches were instructed to avoid intense training 24 h prior to each day of testing. To reduce any interference on the experiment, participants were prohibited from consuming any known stimulant (i.e., caffeine) or depressant (i.e., alcohol) substances for 24 h before testing and were instructed not to eat for 2-3 h before each testing session. Upon each visit the participants underwent a 10 min standardized warm-up (4 min of jogging, 4 min of dynamic stretching exercises, two sprints of 20 m, and jumping drills). After an active recovery (~2 min of walking), participants completed an assessment, consisting of either three CMJs or three shuttle sprints (25m = 12.5m + 12.5m with a 180° COD). Participants consumed water ad libitum during the trials. A single member of the research team administered all tests, such that the potential variation in test instruction was minimized.

Day 1

Jump Test

Lower limb explosive performance was assessed by a CMJ test according to the protocol of Bosco et al. (2). Participants were instructed to keep their hands on their hips to prevent the influence of arm movements. Starting position was stationary, erect, and with knees fully extended. After assuming the starting position, the participants squatted down to about ~90° of knee flexion before beginning a powerful upward motion. Participants were instructed to jump as high as possible and verbal encouragement was provided before each trial. The vertical ground reaction force (GRF) data were collected from a Kistler force plate (Kistler Biomechanics, Winterthur, Switzerland) mounted on a floor apparatus. Sampling frequency was set at 500 Hz and the signal was electronically processed and amplified by a Kistler amplifier (Model No. 9681A). The force platform was regularly checked for accuracy, linearity, and consistency over time in the loaded condition (5 min), using certified weights ranging from 20 to 100 kg. The vertical jump performance (cm) was determined by
using the vertical velocity of the center of mass at takeoff calculated by integrating the vertical GRF through the impulse-momentum method (15). Each athlete performed three trials with passive recovery of 45s between jumps, and the best result was recorded for further analysis.

Calculation of the kinetic variables

The kinetic dependent variables that were measured were peak ground reaction forces (GRFpeak), relative vertical impulse (J), contact time (CT), reactive strength index (RSI), and leg-spring stiffness (kvert). CT was defined as the interval of time beginning with the subject’s downward movement and ending at the moment of takeoff. Specifically, the beginning of the CT was identified when the GRF value reduced about 20-N from the body weight expressed in Newton, while the end-point was when the GRF displayed the zero value. The RSI was calculated by dividing the jump height in meters by the ground CT in seconds. A spring-mass model was used to analyze the vertical kvert, which has been defined as the ratio of the peak force in the spring and the displacement of the spring at the instant that the leg spring is maximally compressed. Accordingly, kvert measures were calculated according to the method of Comyns et al. (6), by dividing the GRFpeak by the displacement of the subject from the initial downward movement to the lowest point of the center of mass during recovery from each CMJ. High-speed video camera data (Casio Exilim FH100, Hi-speed, 240 fps, Tokyo, Japan) was digitized (Kinovea, http://www.kinovea.org) in order to determine the vertical downward displacement of the subject during the jumps. To accomplish this, a passive reflective marker (14-mm diameter) was attached to the skin at the L5-S1 level for sagittal plane analysis. The marker placement at this level was assumed to represent the body movement, and its 2D kinematic raw data was further converted into displacement values (10).

Day 2

25-m sprint test
The 25-m sprint test consisted of a maximal 2×12.5-m shuttle sprint (Figure 1) assessed by using the same setup previously described by Dello Iacono et al. (8). This test has been determined as reliable for monitoring the sprinting and agility activities in handball players displaying excellent agreement between the test-retest measurements and low intra-test variability (95% ICC ranging between 0.943 and 0.992; CV% ranging between 0.91% and 3.58%). The subjects sprinted linearly from the start line (A point – Figure 1) for 12.5 m, touched a line on the floor (C point – Figure 1) with a foot and then, following a 180° change of direction, returned to the start line, all performed as fast as possible. Before sprinting, the subjects were asked to assume the start position, with the front foot placed 5 cm before the first timing gate. Strong verbal encouragement was provided to each subject during all sprints. Time was recorded using photocell gates (Timing-Radio Controlled, TT-Sport, San Marino, Italy) placed at the start-finish points and on the 10-m lines, approximately 0.5 m above the ground, and with an accuracy of 0.001 s. The above setup allowed to calculate three scores for the sprint test: the 10 m in-line performance (A-B distance - the first linear 10 m from the start point), the agility performance or COD times (B-C-B distances - the time for the 2×2.5 m turn-around, between the 10 m and 15 m crossing lines), and the total sprint time (A-C-A distance - sprint, sec). During each test, some temporal kinematic variables were calculated from simple video analysis on the sagittal plane. Specifically, a camera (Casio Exilim FH100, Hi-speed, 240 fps, Tokyo, Japan) was located on a 1.5 m high tripod, 7 m from the running lane, and perpendicular to the acquisition space and the subjects’ plane motion (32). As for the calibration step, the running lane was taped with kinematic markers placed at 5 m length intervals. The film sequences were analyzed off-line using the Kinovea software (http://www.kinovea.org). Each athlete performed three trials with passive recovery of 2 min between sprints, and the best results were recorded for further analysis.

FIGURE 1 ABOUT HERE
Calculation of the kinematic variables

The kinematic dependent variables measured for the 25-m sprint test were:

- Step length (SL): the horizontal distance between the point of touchdown of one foot to that of the following touchdown for the opposite foot;

- Step frequency (SF): steps taken per second. Step frequency was calculated as the inverse of step time (1/step time), where step time was estimated as the time between touchdown of one foot and touchdown of the opposite foot;

- Contact time (CT): the time of the contact phase for both sprinting steps and COD foot step (COD CT).

In accordance to the standard calibration method used in this study (31), the accuracy of the measurements were 2.8 mm and 0.04 s for SL and CT, respectively.

Training Intervention

Training started one week after the baseline testing and consisted of two sessions per week (on Sundays and Wednesdays) of either VDJ or HDJ performed over a period of ten consecutive weeks. This schedule comported the last week of training to coincide with the final weekly micro-cycle of the first round before the winter break (according to the local federation calendar). In addition, both training programs were structured according to a gradual progress plan that included a 7-day tapering period (34) (i.e., total training volume was reduced by 30%), with the aim of both maximizing the final performance and avoiding any negative influence on the following training cycles (Table 1). Participants performed 5-8 sets × 6-10 repetitions of vertical-alternate one-leg or horizontal-alternate one-leg drop jumps, landing from the top of a platform 25-cm in height according to the protocol previously described by Dello, Iacono et al. (8). The rest period between repetitions and sets was 10 and 120 seconds, respectively. The athletes were instructed to place their hands on their hips and step off the platforms with the supporting leg straight
to avoid any initial upward propulsion or sinking, ensuring a drop height of 25 cm (Figure 2). Participants were required to jump for maximal height (VDJ) or maximal horizontal frontward distance (HDJ) through minimizing their contact time with the ground, with every jump performed to maximize reactive strength (i.e., bounce drop-jumps). One researcher and one coach supervised all exercises, and particular attention was paid to the demonstration with maximal motivation given to the athletes during each jump. The length of time of the protocol, including the rest intervals and duration of the jumps, ranged between 15 and 30 minutes.

In addition, to isolate the effect of the current two training protocols, other fitness training sessions (e.g., technical, tactical, and strength) were conducted identically in both groups during the ten weeks of the study. Specifically, the average total training time for each group was ~12 hours per week, including similar technical, tactical strength, and basic skills' drills. Strength training included two sessions/week of upper limb exercises (bench press, shoulder press), with an average load of 50% of 1RM, 3 sets for each exercise with 2 min of passive recovery in-between (8÷10 fast repetitions, “<1 sec), recovery between reps (2 sec), and work-to-rest ratio=1:3 .

**FIGURE 2 ABOUT HERE**

**Statistical Analysis**

All data are presented as means ± standard deviation (SD) and standard error (SE). The Shapiro-Wilk test was used to ensure normal distribution of the results. The ICC and CV were used to determine the reliability and the repeatability of the measures (19). The effect size ($\eta^2$) was calculated for all variables between each condition. A paired sample *t*-test was used to detect differences between pre- and post-test means within each group. Analysis of variance (ANOVA) for repeated measures was used to examine the data for between-group differences at the pre- and post-intervention time points, in order to determine the interactive effects of training protocols. The independent variables included one within-subjects factor (time), with two levels (pre-intervention,
post-intervention) and one between-subjects factor (treatment) with two levels (VDJ vs. HDJ). **When a significant F value was achieved, Tukey’s post hoc procedures were performed to locate the pairwise differences between the mean values.** The following dependent variables were analyzed:

a) Performance variables: height of jumps in the CMJ test, 10-m time, COD time, and total sprint time in the 25-m sprint test.

b) Kinetic variables: GRF\textsubscript{peak}, J, k\textsubscript{vert}, CT, RSI in the CMJ.

c) Kinematic variables: SL, SF and CTs for the 10-m sprinting performance, COD CT of the last footstep.

The alpha test level for statistical significance level was set at \( p \leq 0.05 \). Statistical analysis was performed using SPSS Statistics 21 software (SPSS Inc., Chicago, IL, USA).

**RESULTS**

Tables 3, 4 and 5 show the results of the two conditions for the performance, kinetic and kinematic parameters of the CMJ and 25-m sprint tests, respectively. At baseline (pre-test points), all the variables showed highly reliable data, with ICC ranging from 0.911 and 0.942 for performance parameters, from 0.888 and 0.915 for kinetic measures, and from 0.875 to 0.925 for the kinematic values (Table 2). At the pre- and post-test intervention points, all the dependent variables showed highly reliable intra-test data, with low CVs (ranging from 2.15 to 3.91\%) (Table 2).

Between-groups ANOVA showed no significant baseline anthropometric, performance, kinetic or kinematic differences between the groups for all measurements, with all \( p > 0.05 \).

**Both groups significantly improved in the 10-m sprint time (\( p = 0.004 \) and \( p = 0.002 \) for VDJ and HDJ, respectively) and in the CMJ (\( p = 0.001 \) and \( p = 0.003 \) for VDJ and HDJ, respectively) from pre-test to post-test (Table 3).** As for the kinetic variables, both groups produced increased responses for GRF\textsubscript{peak} (\( p = 0.001 \) and \( p = 0.004 \) for VDJ and HDJ, respectively) and Impulse (\( p = 0.001 \) and \( p = 0.004 \) for VDJ and HDJ, respectively) from pre-test
to post-test (Table 4). In addition, the kinematical variable step length also was increased from pre-test to post-test (Table 5) in both groups \( p=0.003 \) and \( p=0.001 \) for VDJ and HDJ, respectively).

Between-groups ANOVA of the CMJ test showed significant differences as effect of treatment between the two conditions \([F(1,17)=10.977, p=0.004 (\eta^2=0.407)]\). Between-groups ANOVA of the 10-m performance time showed significant differences as an effect of treatment (VDJ vs. HDJ) with \( F(1,17)=9.161 \) and \( p=0.004(\eta^2=0.629) \). The COD performance significantly differed between groups as an effect of protocol (HDJ) interaction with \( p<0.001, \) and \( F(1,17)=54.725 \) and \( p<0.001 (\eta^2=0.774) \). Between-groups ANOVA of the sprint time showed that significant differences were found between the two protocol conditions as effect of treatment (VDJ vs. HDJ) with regard to the sprint time \( F(1,17)=10.004 \) and \( p<0.001 (\eta^2=0.948) \).

Significant between-group differences were found with regard to GRF\(_{peak}\) \( F(1,17)=7.181 \) and \( p=0.004 (\eta^2=0.821) \), relative impulse \( F(1,17)=5.776 \) and \( p=0.008 (\eta^2=0.731) \), kvert \( F(1,17)=10.032 \) and \( p<0.001 (\eta^2=0.992) \), CT \( F(1,17)=5.872 \) and \( p=0.003 (\eta^2=0.687) \), RSI \( F(1,17)=6.124 \) and \( p=0.002 (\eta^2=0.782) \).

Finally, between-groups ANOVA showed significant kinematic differences as effect of treatment for SL 0-1 \( F(1,17)=5.781 \) and \( p=0.007 (\eta^2=0.833) \), SL 2-4 \( F(1,17)=10.032 \) and \( p<0.001 (\eta^2=0.992) \), COD CT \( F(1,17)=8.994 \) and \( p<0.001 (\eta^2=0.923) \).

**TABLES 2, 3, 4 AND 5 ABOUT HERE**

**DISCUSSION**

The present study used a specific field assessment and a controlled design to compare the effectiveness of two drop-jump-based plyometric protocols on performance and biomechanical aspects of jumping, sprinting, and COD performances in elite handball players during the mid-phase of the competitive period. Firstly, the results indicated that both training approaches led to significant
improvements in all the performance variables after a 10-week intervention. Secondly, our outcomes showed different and specific adaptations to each training regimen. Greater improvements in short linear sprint and COD were observed after HDJ, whereas CMJ measures improved more after VDJ. These chronic effects on the explosive performances were further supported by the specific biomechanical variables assessed.

In accordance to our hypotheses, the VDJ led to superior effects on vertical jumping ability when compared with the HDJ (Table 3). Our results are in agreement with a number of previous studies that analyzed the role of vertical GRF among the biomechanical features of vertical jumps (28,37,38). As is well known, the success of vertical jump is determined by the velocity at take-off. From Newton’s second law of motion \( F \cdot \Delta t = m \cdot \Delta v \), this velocity is determined by the preceding impulse \( F \cdot \Delta t \) generated by an athlete. As shown in our data (Table 4), following the VDJ the athletes were able to generate higher amounts of GRF in shorter CT, thus confirming the impulse-momentum relationship and the perfect correlation between the magnitude of the impulse, the velocity at take-off, and the jump height (44). In fact, the VDJ protocol increased the athletes’ ability to apply a greater level of force against the ground during the CMJ assessments, thus reconfirming the rationale about the importance of vertical GRF as a key kinetic component for vertical explosive actions. These findings are further supported by the underlying specific kinetic acute adaptations observed in the CMJ task following the VDJ protocol in comparison with the HDJ (Table 4). In response to the VDJ regimen, jumps were performed with higher relative impulse values that, coupled with the increase in RSI and leg-spring stiffness, indicated that the SSC behavior was enhanced, as is evident from the improvement of the functional performance measures of CMJ (Table 3). In accordance with the theory of specific training overload, in addition to the greater mechanical loading induced by the VDJ forms in comparison with that of the HDJ, a possible explanation for the greater improvement on CMJ performance after VDJ training may be the evident presence of training exercise specificity between this exercise and the CMJ test. In fact, when undertaking specific training to enhance performance outcome in a given task, compared with general conditioning to improve
underlying neuromuscular ability, it is important to utilize exercises that provide a neuromuscular overload in a manner that is task specific. From a methodological perspective, the main characteristic differentiating the two training protocols designed in our study was represented by the axis-force orientation (Figure 2). Therefore, lower conditioning exercise specificity of the horizontal drop-jumps in comparison with the vertical ones and with the CMJ task, should be acknowledged. As a consequence, performing vertical drop-jumps repeatedly may have increased the chances for the VDJ group to make greater adaptations, considering the importance of vertical force production and its application in jumping performance (38). On the other hand, concurrent increases in CMJ jump height were also observed following the HDJ protocol (Table 3). Vertical and horizontal one-leg jumps are commonly reported as independent tasks featuring different leg strength/power qualities. However, Meylan et al. (30), investigating the interrelationship in vertical and horizontal jump assessments, have found moderate correlation (r=0.64) and a shared variance of about 45% between single-leg vertical and horizontal jump tests. In this context, a recent investigation of Dobbs et al. (13) has provided interesting data with regard to the biomechanical responses of vertically- and horizontally-oriented drop-jump tasks. Specifically, the comparison of the kinetic variables showed much greater magnitude of peak vertical GRFs (≈ 5 times) during the vertical drop jump forms compared with the horizontally-oriented ones. Nevertheless, unilateral horizontal drop jumps performed from a landing height of 20 cm produced peak and mean impulses similar to those occurred in the vertical task (13). Consequently, it is reasonable that this mode of plyometrics induced a moderate but sufficiently effective mechanical stimulus that in the long-term, has led to positive adaptations for the vertical performance direction. Although this study is the first to determine the effect of specific plyometric methodologies on consequent vertically- or horizontally-oriented performances of elite athletes, the current results are in agreement with those of previous investigations that have generally demonstrated 5-15% improvements in vertical jump height (25) due to a combination of enhanced neuromuscular activities and greater muscle mechanical outputs after training.
The second finding of the present study was that both training regimens led to specific improvements in the horizontally-oriented explosive performances, but the HDJ group resulted in larger gains in comparison with the VDJ group (Table 3). The 25-m sprint test, including both in-line short distance (10-m) sprint and COD tasks, had the particularity to assess the specific initial acceleration and agility ability in handball players (3,8). Both initial acceleration and agility have been found to be powerful discriminators of elite handball players and therefore should be used as descriptive tests for handball performance (17,33). The distance of 10 m appeared to be the most relevant to assess the specific quality of acceleration in handball because of the high frequency of short, high-intensity sprints during a game (42). A significant greater decrease in 10-m sprint time in the HDJ (8.5% vs. 4% for HDJ and VDJ, respectively) (Table 3) demonstrated the efficiency of a specifically-oriented plyometric program to improve short-distance explosive actions of elite handball players. The percentage of changes in performance after a 10-week training period in the current study, is in agreement with those of previous investigations designed for similar types of training for adult (16,18) and adolescent (5) handball players which reported beneficial effects on agility and sprinting performance. Initial acceleration has been shown to be more difficult to enhance due to the smaller margin for improvement and the different forces involved. Therefore, the outcomes in the current study offer insights into the possibility of practical applications of training regimens similar to the designed HDJ given that they could provide players with a physical advantage over equally skilled opponents towards the critical phases of the game. Previous reports have tried to identify the key mechanical factors for successful performance in short-distance sprints (7,22,45). Kawamori et al. (22), highlighted that net horizontal GRF impulse normalized to body mass was the major determining kinetic factor of the change in the horizontal velocity of the athlete during ground contacts of sprint tasks. However, simply attempting to maximize net horizontal GRF impulse may result in longer ground CT and lower SF, which could be detrimental to sprint acceleration performance. In fact, sprinting velocity is the product of SL and SF (29). Thus, to improve sprinting velocity, athletes need to improve at least one of these factors while the other factor remains
unchanged or reduces, to a lesser extent the gain in the former. In our study, following 10-week plyometric training, all athletes performed short-distance sprints through a different strategy in terms of temporal kinematic parameters. Specifically, no changes in CTs and SF were observed at post-intervention point for both groups, while SL was significantly longer with a greater increase for the HDJ group in comparison to the VDJ one (Table 5). In light of these results, it was not surprising that SF was unchanged, because no significant change occurred for CTs (20). The concurrent outcomes highlighting no pre- vs. post-intervention changes for CTs and SF associated with improved 10-m sprint performances, may be attributed to the athletes’ ability to produce greater horizontal forces for an optimal propulsive action. In this regard, the interactions between SL and SF and their influence on sprinting performance have been widely investigated (20). Several authors (20,43) have proposed that the greatest determinant of sprinting velocity is SL, which, in turn, is most highly related to the magnitude of the horizontal ground-reaction impulse. Therefore, an optimal combination of the magnitude, direction, and duration of GRF is required for maximizing sprint acceleration performance. Considering this background, it is worth noting that, after the 10-week intervention, significant interaction effects (time × intervention) leading to greater improvements in short-distance sprinting performance, were directly attributable to the HDJ regimen (Table 3). Consequently, players performing HDJ benefitted more from the favorable effect of specific horizontally-oriented drop-jumping training on leg force production and proper application onto the ground that, in turn, induced better sprint performances. This conclusion is further supported by the evidence that concurrent greater changes in SL values were observed in HDJ when compared with VDJ (Table 5).

Outcomes from the present study also revealed that the HDJ regimen led to specific improvement in the horizontally-oriented COD performance, and resulted in larger gains in comparison with the VDJ protocol (Table 3). Our findings are in agreement with the study of Dello Iacono et al. (10), who reported similar acute performance improvements of the same COD cutting task due to an horizontally-oriented drop-jump based PAP protocol. Moreover, the results of Meylan
et al. (30), support our findings, in that they have reported horizontally-oriented jump task assessment as the single best predictor ($r = -0.46$ to $-0.59$) of COD performances similar to those involved in our study. Our data highlight a main effect of the HDJ application on the biomechanical parameter COD CT of the cutting maneuver required during the COD task (Table 5). Following a 10-week period of HDJ training, the athletes were able to reduce the ground CT of their plant step in completing the COD by about 12.1% (Table 5) with an improved performance time of 8% (Table 3). Our results are similar to those of Sasaki et al. (39), and Marshall et al. (27), which also found ground CT ($p \leq 0.05$ and $p < 0.01$, respectively) significantly correlated with cutting time ($r = -0.65$ and $r = -0.48$, respectively). Although many muscle groups are involved in the multi-joint action of cutting, shorter ground CT should be given greater emphasis, suggesting that the plant leg must demonstrate significant control under deceleration in a cut, in order to facilitate efficient SSC utilization and to achieve optimal performance. In fact, to produce a fast COD, it would be desirable to achieve a relatively short ground CT that initially facilitates the eccentric deceleration of the downward motion of the body’s center of mass and consequently produces a propulsive phase. For instance, the performance of COD tasks has been associated with the athletes’ ability to transfer the linear momentum of force directly from the ground to the peak horizontal acceleration of the body’s center of mass, which is critical to break the inertia (i.e., starting from a zero-velocity (24)). The results of the present study revealed how athletes performed quicker COD tasks combined with shorter ground COD CT after performing the HDJ protocol, compared to the VDJ regimen (Tables 2 and 5). Thus, the concomitant occurrences of such performance and kinematic responses (shorter COD time and COD CT, respectively) suggest that both higher amount of horizontal GRF and optimal horizontal-to-vertical force ratio may represent the specific biomechanical adaptations that, in turn, have led to greater COD performance following HDJ protocol in comparison with the VDJ. Moreover, the specific body configuration required during the landing task of both protocols, may have produced short-term transference effects of the subsequent vertically- and horizontally-oriented tasks (Figure 2). Kugler and Janshen (23) found significant correlations ($p<0.05$) between forward oriented GRF
associated with forward oriented body positions and higher accelerations; briefly, individuals who exhibited a greater inclination of their torso in the sagittal plane toward the direction of the finish line, coupled with higher amounts of the propulsive force component, tended to have faster performance times. From a methodological perspective, the main and only characteristic differentiating the two training protocols designed in our study was that the conditioning stimulus was either vertical or horizontal in nature. Therefore, the similarities and specificities between the HDJ exercise and the agility maneuver may have increased the chances for the HDJ group to make greater adaptations, considering the importance of horizontal force production combined with the specific whole body biomechanical configuration and its application to COD performance (38).

In conclusion, the development of large forces upon conditioning exercises is a fundamental requisite for inducing neuromuscular adaptations (37), muscle remodeling (1,16,37) and functional enhancements of athletic tasks (38). However, competitive performance depends not only on strength but also on the ability to exert such forces both at a specific rate and through an orientation similar to those required by the mechanical demands of each sportive discipline (29). In other words, it seems that the importance is not only referred to the amount of total force produced, but also the way it is oriented onto the supporting ground when performing specific tasks (23). The results of this study can guide conditioning specialists in choosing the training means that best generate the acute and optimal physiological conditions for consequent task enhancement and, in turn, practical means to train athletes efficiently. **On the other hand, the combination of exercises aiming to develop both vertical- and horizontal-component axis forces has a logical training construct in professional handball neuromuscular performance development.** Considering the findings of the current study, it could be hypothesized the superiority of combined training protocols over isolated training regimens for the overall athletic development of elite handball players. Therefore, further studies are needed to obtain evidence of the optimal combination (i.e., combined vertical and horizontal conditioning regimens) and training dose of exercises (i.e., proportion of vertical and horizontal exercises) required for effective neuromuscular abilities.
PRACTICAL APPLICATIONS

In light of the chronic performance and biomechanical adaptations associated with the vertically- and horizontally-oriented conditioning regimens examined in the current study, it is proposed that specific plyometric protocols may induce transference effects in enhancing related performance outcomes. Plyometric training could be prescribed as specifically oriented exercises, which improve explosive force production and functional performance according to the specific sport-task and the biomechanical demands. Specifically, VDJ training, applied during 10 weeks, achieved greater improvement in vertically-oriented explosive performance assessed by vertical jump compared to HDJ. Conversely, HDJ elicited greater gains in horizontally-oriented functional tasks such as short-distance sprint and COD. Consequently, during the in-season period, handball coaches may integrate these conditioning methodologies into their training strategies, given that they represent a viable means for inducing specific functional adaptations and in turn, for achieving enhanced performance levels.

References


Conflict of Interest:
The authors have no conflict of interest to declare.

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The results of the present study do not constitute endorsement of the product by the authors or the NSCA

FIGURE LEGENDS

Figure 1. 25-m sprint test setup

Figure 2. Vertical (Upper) and horizontal (Lower) drop-jump training protocols