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Biomechanical differences of arm swing countermovement jumps on sand and rigid surface performed by elite beach volleyball players

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ABSTRACT
The purpose of this study was to investigate the possible arm swing effect on the biomechanical parameters of vertical counter movement jump due to differences of the compliance of the take-off surface. Fifteen elite male beach-volleyball players (26.2 ± 5.9 years; 1.87 ± 0.05 m; 83.4 ± 6.0 kg; mean ± standard deviation, respectively) performed counter movement jumps on sand and on a rigid surface with and without an arm swing. Results showed significant (p < .05) surface effects on the jump height, the ankle joint angle at the lowest height of the body center of mass and the ankle angular velocity. Also, significant arm swing effects were found on jump height, maximum power output, temporal parameters, range of motion and angular velocity of the hip. These findings could be attributed to the instability of the sand, which resulted in reduced peak power output due to the differences of body configuration at the lowest body position and lower limb joints’ range of motion. The combined effect of the backward arm swing and the recoil of the sand that resulted in decreased resistance at ankle plantar flexion should be controlled at the preparation of selected jumping tasks in beach-volleyball.

Introduction
Volleyball and beach-volleyball (BV) are sports dominated by skills (i.e. block, spike, jump serve, overhead set with a jump) where jumping is an essential component. The development of BV from a recreational to an Olympic sport has provoked the interest concerning the adaptations of volleyball and BV players after training on sand. Previous research indicates that training on sand can increase the applied training load, which can be manipulated without modifying the training volume (Binnie, Dawson, Arnot et al., 2014). Training on sand is associated with a lower risk of injury due and advanced capacity for performance in consecutive training days due to the lower impact forces experienced on the sand (Binnie, Dawson, Pinnington, Landers, & Peeling, 2014; Gaudino, Gaudino, Alberti, & Minetti, 2013). In general, the adaptations of sand training is suggested to be transferred to indoor performance (Gortsila, Theos, Nesci, & Maridaki, 2013; Impellizzeri et al., 2008; Trajkovic, Sporis, & Kristicic, 2016). On the other hand, a disadvantage of sand training is the decrement of maximum movement speed, a factor that results in decreased effectiveness of training programs that aim to improve performance in activities enabling the stretch-shortening cycle (Binnie, Dawson, Pinnington et al., 2014).

Because of the significance of jumping for the game, vertical jumping tests are considered as essential conditioning tests to evaluate performance of volleyball and BV players (Aouadi et al., 2012; Bishop, 2003; Ricarte Batista, Freire De Araujo, & Oliveira Guerra, 2008; Sheppard & Newton, 2012; Ziv & Lidor, 2010). The vertical jump with a countermovement (CMJ) is considered to be the most appropriate test to evaluate the physical requirements involved in volleyball skills (Sheppard & Newton, 2012). A vast majority of the jumps performed in BV are characterized by the countermovement and the arm swing (Turpin, Cortell, Chinchilla, Cejuela, & Suarez, 2008). In specific, the stationary CMJ is observed during blocks, standing jump float serve and special counter attack actions (Giatsis, 2001). The countermovement is proposed to increase the lower limb muscle’s active state, which enables the increase of the positive muscle work during the ascent phase, thus allowing the athletes to achieve a greater jumping height compared to a vertical jump initiated from a stationary squatting position (Bobbert & Casius, 2005; Bobbert, Gerritsen, Lijtjens, & van Soest, 1996; Voigt, Simonsen, Dyhre-Poulsen, & Klausen, 1995). Nevertheless, a larger jumping height in a range of 6–30% has been observed when a CMJ is executed with an arm swing (Caruso et al., 2012; Domire & Challis, 2010; Feltner, Bishop, & Perez, 2004; Harman, Rosenstein, Frykman, & Rosenstein, 1990; Lees, Vanrenterghem, & De Clercq, 2004a; Richter, Rapple, Kurz, & Schwameder, 2012; Shetty & Etnyre, 1989; Vanezis & Lees, 2005; Walsh, Waters, Bohm, & Potteiger, 2007). This increase of vertical jump performance when an arm swing is used is believed to be the outcome of the increased load imposed on the leg muscles because of the mechanical work produced by the upper limb joints combined with higher lumbar spine joint work due to the greater hip extensor torques resulted by the slower rate of hip and lumbar spine extension (Blache & Monteil, 2013; Feltner, Fraschetti, & Crisp, 1999; Hara, Shibayama, Takeshita, Hay, & Fukashiro, 2008; Vanezis & Lees, 2007).
The latter results in larger force, power and work outputs compared to the non-arm swing CMJ (Harman et al., 1990; Shetty & Etnyre, 1989). Another issue to be argued for the assessment of CMJ is the surface where the push-off is executed, because surfaces of different materials have been found to alter jumping performance (Giatsis, Kollias, Panoutsakopoulos, & Papaiakovou, 2004; Miyama & Nosaka, 2004). For example, BV players were found to have lower vertical jumping heights when jumping on a sand surface compared to a rigid one (Bisciotti, Ruby, & Jaquemod, 2001; Bishop, 2003; Giatsis et al., 2004; Muramatsu, Fukudome, Miyama, Arimoto, & Kijima, 2006). The compliance of the sand imposes a constraint for an efficient coordinated extension action of the lower limb joints and requires higher energy expenditure in order to fulfill the demand of maintaining postural stability (Muramatsu et al., 2006; Smith, 2006). This results in a reduced force application and less power production during the propulsion for jumping from a sand surface (Bisciotti et al., 2001; Bishop, 2003; Giatsis et al., 2004; Impellizzeri et al., 2008).

Despite the fact that the arm swing effect on a CMJ has been thoroughly investigated on a rigid surface, no studies investigating the effect of the arm swing on a CMJ executed on a sand surface were found in the relevant literature. The purpose of the present study was to examine the possible performance outcome differences and the biomechanical adaptations due to the sand surface when a CMJ is performed by elite BV players with and without the use of an arm swing. The effect of the sand surface was studied by comparing the differences of CMJ with and without an arm swing performed on a sand surface with the observed differences of respective CMJ executed on a rigid surface. The above comparison was used in order to test the hypothesis that the differences observed between CMJs executed with and without the use of an arm swing will be unaffected by the constraints imposed by the sand surface. The results of the study could reveal useful information for practitioners to better plan training protocols including CMJ with an arm swing executed on sand surface.

Methods
Participants
Fifteen elite male BV players (age = 26.2 years ± 5.9; height = 1.87 m ± 0.05; mass = 83.4 kg ± 6.0) volunteered to participate in the present study. Inclusion in the study required a recent participation in an international FIVB tournament. Participants were selected for the study because they were familiar with both experimental jumping surfaces and were assumed to be able to execute vertical jumps on a rigid (RIGID) and sand (SAND) surface with a small variability in performance (Busca et al., 2013; Kollias, Panoutsakopoulos, & Papaiakovou, 2004; Sattler, Sekulic, Hadzic, Uljevic, & Dervisevic, 2012). All participants had no apparent or reported injury or disability and had previous experience in the execution of vertical jumps in the laboratory. Informed consent was obtained from the athletes in order to participate in the study, which was conducted according to the 2000 revision of the Declaration of Helsinki for the use of human subjects and was approved by the Institutional Research Committee Board (approval no.: 104291/2013).

Procedure
After a typical 20-minute warm-up, which included 10 min cycling on an 817E Monark Exercise Cycle (Exercise AB, Vansbro, Sweden) at constant velocity of 5.5 m.sec\(^{-1}\) with 0 W load and 10 min dynamic stretching exercises, consisting of easy movements that gradually engaged the joints to move in almost full range of motion. A section of self-administered sub-maximal jumps performed for familiarization and additional specific warm-up followed. Prior to beginning of the testing session, the participants were instructed in the execution of the counter movement jumps with and without arms. At the starting position, participants were at stationary upright position. For the CMJ with an arm swing (AS), the arms were hanging freely at the side of the body and were then swung backwards and forwards during the propulsion phase. In the case of the CMJ without the use of the arms (NAS), the arms were placed on the hips throughout the jump, the flight and the landing. The instruction given to the participants was to “jump as high and as fast as possible”, without posing limitations concerning the magnitude of the knee flexion during the countermovement. All jumps were performed barefooted (Figure 1).

Subjects performed six CMJ for each of the surface conditions, three AS and three NAS, in a random counterbalanced order. A minimum of a 60-sec resting period was allowed
between trials in order to avoid fatigue. With the completion of the jumps on RIGID or SAND, a 10-minute rest was given before the execution of the jumps on the alternate surface. During this period, participants were given a chance to perform additional jumping trials for familiarization with the new surface. The best attempt of the three trials, using as criterion the maximum jump height achieved (JH), was selected for further analysis.

**Experimental instrumentation**

**Sandpit**
The vertical jumps on RIGID condition were executed on the force plate. In order to execute vertical jumps on SAND, a wooden pit (bottom side dimensions: 46 x 50 cm; upper side dimensions: 59 x 63 cm; depth: 31 cm) was constructed to contain the sand particles (Figure 2). The sandpit was attached exactly on the force plate, since both of them had the same dimensions. Before the actual testing, it was established that the mass of the participants recorded from the force plate was absolute the same with and without the sandpit.

The edges of the sandpit were covered with soft materials in order to protect the participants during faulty landings. A canvas sheet was placed far from the sandpit and covered the surrounding safety platform (116 x 150 x 31 cm), which was also used to hold the sand particles in. The total weight of the wooden pit, including the sand, was 120.12 kg.

**Sand analysis**
The sand used in the conducted tests was collected from a beach that was used for the national beach volleyball tournaments. It must be noted that the sand was free from any organic material and that the sand’s physical properties and particle size distribution satisfied the FIVB requirements for the conduction of official beach volleyball tournaments (Federation International de Volleyball [FIVB], 2013). In terms of origin it could be described as a beach alluvial deposit derived from the mechanical weathering of the sandstone-marl series geological formations of the nearby area. It was soft due to its marl origin and round shaped due to the processes of natural weathering that it sustained. The physical properties and grain size distribution of the sand tested were determined from laboratory tests according to ASTM (American Society for Testing and Materials) that were carried out at the Laboratory of Engineering Geology of the Institutional Department of Geology.

The natural moisture content of the samples ranged from 3.2% – 7.5% (American Society of Testing and Materials [ASTM], 2005; D2216-05) and the density was 1900 kg/m³ (ASTM, 2009; C29 / C29M-09). The grain size distribution was carried out according to the Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (ASTM, 2014; C136 / C136M-14). Results showed that 83.5% of the particles size ranged between 0.25–1.0 mm, and only a 4.1% was coarse sand (particle size between 1.0–2.0 mm). A 10.5% was fine sand (0.15–0.25 mm) and the rest (1.9%) was very fine sand (0.05–0.15 mm). The dry unit weight of the sand (yd) was calculated as 13.5 kN/m³ and the void ratio (e) was 0.96. The compaction curve for the sand was determined by the Modified Proctor test specification (ASTM, 1991; D1557-91), resulting to a maximum dry unit weight of the sand (yd_{max}) of 17.18 kN/m³ at an optimum water content (m_{op}) equal to 13.5%. The equivalent minimum void ratio (e_{min}) was 0.54. From the test results the relative density (D_r) of the sand was estimated using the following Equation (1)

\[ D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100\% \]  

where \( e \) is the void ratio, \( e_{min} \) is the minimum void ratio and \( e_{max} \) is the void ratio corresponding to the loosest possible state of the soil, usually obtained by pouring the soil into a mold of known volume (ASTM, 1998; D4254-96).

The value of \( D_r \) strongly affects the engineering behavior of the soil and was estimated as \( D_r = 8.7\% \) for a value of \( e_{max} = 1 \). In terms of firmness or degree of compaction, the sand was classified as very loose sand according to Lambe and Whitman (1979), since \( D_r \) was less than 15%. As for the soil stiffness, it can be expressed by the value of Soil Young’s modulus (E), commonly referred to as soil elastic modulus. This can be estimated in laboratory or in-situ tests or based on correlation with other soil properties. Typical values of Young’s modulus for granular material (MPa) can be estimated based on Orzbuz (2010; compiled from Kezdi, 1974; Prat, Xiao, Ausiello, & Cantiello, 1995). In general, the soil stiffness and elastic modulus depends on the consistency and packing (density) of the soil. The stiffness of the sand used in the present study was estimated as \( E = 9806 \) kPa.

**Procedure to ensure the firmness of the sand surface**

For the avoidance of surface penetration and compaction, the sand was well turned up prior to each SAND test. For this procedure, a custom sharp tool was used, which had a mark at a distance of 31 cm in order to verify the uniform distribution of the sand within the sand pit and to visually check that the

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**Figure 2.** A wooden pit (bottom side perimeter: 46 x 50 cm; upper side perimeter: 59 x 63 cm; depth: 31 cm) was constructed to contain the sand particles. Prior to each SS test, in order to avoid surface penetration and compaction, sand was well turned up by a sharp tool which has a mark at the 33 cm for the optical contact with the bottom of the sand pit and was prepared flat and uniform for the upcoming trial.
depth from the bottom of the sand pit was even. The sand was prepared in a way that the surface level was for the upcoming trial (see Figure 2).

**Data acquisition**

Ground reaction forces (GRF) were recorded with an AMTI mod. OR6–5–1 force plate (AMTI, Newton, MA) connected on line with a Pentium II PC in which GRF recordings were stored after being converted to digital using a PC-LabCard PCL-812PG (Advantech Co., Taiwan) 12 bit analogue-to-digital converter. Data acquisition was set to a nominal sampling frequency of 500 Hz. The signal was digitally smoothed using a 2nd order low-pass Butterworth filter, with cut-off frequency set at 8 Hz.

Trials were also videotaped using a digital JVC GR-DVL 9600 EG (Victor Company, Japan) video camera recording at a sampling rate of 100 fps. The camera was fixed on a stationary tripod which was placed at a height of 1.2 m and at a distance of 7.6 m from the center of the force plate. The camera was placed perpendicular to the plane of motion and recorded the left-sided view of the participants. The calibration of the recorded view was accomplished by placing a 2.5 m × 2.5 m frame with 16 control points within the filming view in order to produce two-dimensional coordinates using a 2D-DLT kinematical analysis method (Kollalias, 1997).

**Data analysis**

The video files were processed with the Adobe Premiere 5.1 software (Adobe Systems Incorporated, San Jose, CA) in order to extract the video-fields. Twelve anatomical points of the body (proximal medial phalanx, tuberosity of the 5th metatarsal, posterior surface of the calcaneus, lateral malleolus, lateral epicondyle of the femur, greater trochanter, 7th cervical vertebra, top of the head, acromion, lateral epicondyle of the humerus, ulna-styloid process, head of the 5th metacarpal) were manually digitized in each field using as reference the markers (1 cm diameter) placed on the participants. The coordinates of the body center of mass (CM) were calculated for every field using the method of segments and the anatomical data proposed by Dempster (1955). A 2nd order low-pass Butterworth filter with a cut-off frequency ranging from 4 to 6.5 Hz, depending on the noise calculated with residual analysis (Winter, 1990), was used for smoothing the data. For reliability calculations, 40% of the kinematic analysis was reanalyzed, therefore surpassing the reference of 10% (Tabachnick & Fidell, 2006). Cohen’s Kappa varied between .82 and 1.00 for intra-observer reliability, fulfilling the criterion of .75 suggested in the literature (Fleiss, Levin, & Paik, 2003).

**Variables**

JH was calculated as the outcome of the BCM vertical take-off velocity computed after the integration of the vertical GRF (Fz). CMJ performance was also evaluated as the vertical BCM displacement from the initial standing position to the apex of the jump (hMAX). The maximum rate of force development (RFD) was extracted as the peak value of the first-time derivative of the recorded vertical GRF. Peak body power output (PMAX) was the peak value of the multiplication product of the vertical GRF by the vertical BCM velocity during the propulsive phase. BCM displacement from the initial starting position to the instant of take-off (h0), from the initial starting position to the instant of the lowest BCM position (S0, the downward phase of the propulsion) and from there up (SUP) to the take-off (i.e. the upward phase of the propulsion) was extracted through integration of the vertical BCM velocity. Peak body work at the upward phase (WUP) was defined as the peak value computed by multiplying the Fz by the vertical BCM displacement. Temporal parameters such as the total duration of the impulse (TC), the duration of the upward phase (TUP) and the time to achieve maximum vertical ground reaction force (TFz) were also examined.

As for the kinematical parameters derived from the video analysis, the ankle (θa), knee (θk), hip (θh) and shoulder (θs) joint angles at the lowest BCM height (θLP) during the impulse and at the instant of the take-off (θTUP) were calculated using the extracted coordinates of the digitized points. The extracted coordinates of the greater trochanter and the 7th cervical vertebra were used to calculate the inclination of the torso with respect to the horizontal axis at the lowest BCM height (ϕTLP). The angular displacement from θLP to θTUP was recorded at the joint range of motion (θROM) during the upward phase of the propulsion. The angular velocity (ω) of the joints was calculated as the first-time derivative of their angular displacement.

The synchronization of the force and kinematical data was accomplished with Lagrange interpolation, using as references the instances of take off, of maximum BCM velocity and maximum BCM acceleration attained from both signals. All data acquisition and analysis procedures were executed using custom made software.

**Statistical analyses**

Descriptive statistics for the examined parameters are presented as mean ± standard deviation. Levene’s test was used examine any significant differences between group variances. A factorial ANOVA was carried out to compare the main effects of surface and kind of CM and the interaction effect between surface and kind of CMJ on force and kinematic parameters. In detail, a 2 (surface: RIGID / SAND) × 2 (arm swing: NAS / AS) repeated measures ANOVA with Bonferroni adjustment was carried out. Effect size (eta squared, η²) was used with values of >.06 and >.15 considered as moderate and large, respectively (Cohen, 1988). Furthermore, a two-tailed paired samples t-test was applied to compare the NAS and AS force and kinematic parameters on RIGID and SAND. Cohen’s d (Cohen, 1988) was computed to find the effect size. The thresholds of these effect sizes were considered as small (≤ 0.39), medium (0.40–0.79) and large (≥ .80). All statistical procedures were conducted using the IBM SPSS Statistics v. 21.0 for Windows software (IBM Corp., Armonk, NY), with the confidence intervals set at 95%.

**Results**

**Force parameters**

The arm swing increased JH by 21.6 and 24.7% at the RIGID and SAND conditions. On the other hand, the CMJ executed on SAND
Figure 3. Differences concerning the take-off height (h0) and the jump height achieved referred to the initial standing position (hMAX) for the counter-movement jumps executed on a rigid (R) and a sand (S) surface, with (AS) and without (NAS) arm swing.

Table 1. Results of the force parameters for the counter-movement jump with (AS) and without (NAS) the use of an arm swing executed on a RIGID and SAND (n = 15).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Jump</th>
<th>RIGID</th>
<th>SAND</th>
<th>Surface</th>
<th>Arm Swing</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump height (cm)</td>
<td>NAS</td>
<td>29.8 ± 5.1</td>
<td>26.3 ± 4.3*</td>
<td>.004†</td>
<td>.137</td>
<td>.001†</td>
</tr>
<tr>
<td>Kinetic parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>peak vertical GRF (N/kg)</td>
<td>NAS</td>
<td>2.53 ± 0.18</td>
<td>2.52 ± 0.21</td>
<td>.828</td>
<td>.001</td>
<td>.150</td>
</tr>
<tr>
<td>RFD (kN/sec)</td>
<td>AS</td>
<td>2.60 ± 0.16</td>
<td>2.58 ± 0.18</td>
<td>.228</td>
<td>.020</td>
<td>.970</td>
</tr>
<tr>
<td>Peak Power output (W/kg)</td>
<td>NAS</td>
<td>29.1 ± 3.8</td>
<td>27.7 ± 3.7*</td>
<td>.073</td>
<td>.056</td>
<td>.001†</td>
</tr>
<tr>
<td>Temporal parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration of impulse (ms)</td>
<td>NAS</td>
<td>901 ± 105</td>
<td>923 ± 87</td>
<td>.175</td>
<td>.033</td>
<td>.001†</td>
</tr>
<tr>
<td>Time of upward phase (ms)</td>
<td>AS</td>
<td>1048 ± 144</td>
<td>1121 ± 179*</td>
<td>.006</td>
<td>.940</td>
<td>.067</td>
</tr>
<tr>
<td>Time to achieve maximum F2 (ms)</td>
<td>NAS</td>
<td>336 ± 26</td>
<td>337 ± 37</td>
<td>.323</td>
<td>.017</td>
<td>.001†</td>
</tr>
<tr>
<td>Body center of mass vertical displacement Downward phase (cm)</td>
<td>NAS</td>
<td>−37.3 ± 4.5</td>
<td>−37.7 ± 5.5</td>
<td>.590</td>
<td>.005</td>
<td>.088</td>
</tr>
<tr>
<td></td>
<td>AS</td>
<td>−34.2 ± 7.0</td>
<td>−35.4 ± 6.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upward phase (cm)</td>
<td>NAS</td>
<td>63.6 ± 4.5</td>
<td>61.5 ± 6.8</td>
<td>.151</td>
<td>.036</td>
<td>.135</td>
</tr>
<tr>
<td></td>
<td>AS</td>
<td>66.6 ± 8.0</td>
<td>63.7 ± 6.7*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GRF: Vertical ground reaction force; RFD: maximum value of rate of force development; η²: Effect size, eta squared; thresholds: > .06 moderate, > .15 large; †: significant surface effect (P < 0.05); ‡: significant arm swing effect (P < 0.05); ††: significantly different from the rigid surface (P < 0.05).
AS-CMJ and the larger RFD occurred on SAND. It is worth noting that RFD was considerably higher on SAND, both in the NAS and AS conditions. Also, small-sized ($d = 0.45$) surface effects were observed as the total duration of impulse was longer on SAND than on RIGID for the AS ($t_{(1,14)} = 2.394, P = .031$).

Figure 4 presents the mean ensemble curves for selected force parameters. A similar pattern between RIGID and SAND conditions was identified for vertical GRF and power. A detailed examination of the curves reveals that vertical GRF peaked about the last 20% of the total duration of impulse in the NAS tests, whereas it peaked about 60% in the AS conditions. Additionally, it was observed that the slope of the power output curve was lower in AS compared to NAS.

**Joint kinematical parameters**

The results of the joint kinematical parameters are presented in Table 2. Significant medium ($d = 0.56$) surface effects were revealed for the ankle angle at the lowest BCM height ($P = .031, \eta^2 = .081$), as it was larger for NAS-CMJ on RIGID compared to SAND ($t_{(1,14)} = 2.458, P = .028$). Furthermore, this angle was significantly ($t_{(1,14)} = 4.001, P = .001$) larger on RIGID than SAND for the AS-CMJ (medium size effect, $d = 0.60$). Significant medium surface effects were also revealed for the peak angular velocity of the ankle ($P = .035, \eta^2 = .077$). A large arm swing effect was revealed as the peak angular velocity of the hip and the shoulder increased in the NAS conditions ($P = .001, \eta^2 = .298$ and $P = .001, \eta^2 = .972$, respectively). An arm swing medium effect was also detected for the hip joint range of motion ($P = .050, \eta^2 = .067$), since larger values were observed for NAS.

On average, participants performed the upward phase of the CMJ with larger ankle joint range of motion on SAND. The ankle joint range of motion was significantly larger on SAND for the NAS ($t_{(1,14)} = 2.309, P = .037, d = 0.45$) and AS ($t_{(1,14)} = 2.759, P = .015, d = 0.32$) compared to RIGID. A medium size surface effect ($d = 0.65$) was also revealed for the hip joint range of motion, since it was significantly ($t_{(1,14)} = 2.517, P = .025$) larger on SAND than RIGID for the AS-CMJ. Finally, a large size surface effect ($d = 0.89$) was revealed for the peak angular velocity of the ankle, since it was significantly ($t_{(1,14)} = 2.645, P = .019$) larger on SAND compared to RIGID for the NAS-CMJ.

Figure 4. Mean ($n = 15$) ensemble curves for vertical ground reaction force (a), Rate of Force Development (b), whole body work output (c), normalized to body mass power output (d), Body Center of Mass vertical velocity (e) and displacement (f), for the countermovement jumps executed on a rigid (R) and a sand (S) surface, with (AS) and without (NAS) arm swing.
The inclination of the torso for the AS-CMJ was significantly larger \((t(1,14) = 2.166, P = .048)\) on SAND than RIGID, but this difference represented a small-sized effect \((d = 0.35)\). No surface or arm swing effects \((P > .05)\) were found concerning the other kinematic parameters. Additionally, no interaction was shown to be significant \((P > .05)\).

During the upward phase, a proximal-to-distal joint extension sequence was observed in all experimental conditions. Despite the fact that the lower limb joints’ angular displacement followed an identical pattern between AS and NAS tests, Figure 5 reveals that these joints are less flexed during the downward phase of the SAND-AS tests along with a more
upright torso position. Additionally, a similar pattern between RIGID and SAND conditions was also observed for the angular velocity of the ankle, knee and hip joints (Figure 6). However, during the downward phase of the NAS conditions, the angular velocity of the knee and the hip converged to a lower value faster in comparison with the AS conditions. As for the hip joint, both the extension and flexion angular velocity values were larger on SAND compared to RIGID. Despite the fact that the curves presenting the angular velocity of the shoulder were identical in the upward phase of CMJ on SAND, differences occurred in the downward phase. This is notable as a single, larger peak was observed on SAND at the middle of the downward swing, as opposed to the double, lower peaks observed on RIGID tests at the same phase. In general, extension angular velocity peaked earlier compared to RIGID-NAS when the CMJ utilized AS or when it was executed on SAND.

Discussion

Results revealed a combined surface and arm swing effect for jump height, power and hip range of motion. An arm swing effect was detected for the total duration of impulse, the time to achieve maximum vertical GRF, the vertical BCM displacement during the downward and upward phases, the peak angular velocity of the ankle, knee and hip joints, while the compliance of the surface (SAND versus RIGID) resulted in differences for the angle at the lowest position and the range of motion of the ankle joint. Based on the data of the present study, the execution of CMJ with an arm swing on a sand surface by the examined beach volleyball players was characterized by a longer propulsive phase and by a larger mobilization of the hip joint.

It is well documented that the use of the arm swing increases JH because the AS-CMJ is found to be related with increased force application, power production and work output compared to NAS-CMJ (Cheng, Wang, Chen, Wu, & Chiu, 2008; Feltner et al., 1999; Hara et al., 2008; Harman et al., 1990; Shetty & Etnyre, 1989; Walsh, Bohm, Butterfield, & Santhosam, 2007). This is in agreement with the findings of the present study. The vertical GRF patterns observed in the present study were similar to those observed previously (Feltner et al., 2004; Lees et al., 2004a).

As for the kinematical parameters, the peak angular velocity of the knee and the hip were lower in NAS compared to AS, as also found in relevant studies (Cheng et al., 2008; Feltner et al., 1999; Lees et al., 2004a). Additionally, non-significant lower peak angular velocity of the knee was observed on SAND than on RIGID, verifying similar results found in the literature (Arianasab, Mohammadipour, & Amiri-Khorasani, 2017; Giatsis et al., 2004). It has been proposed that the restriction of the angular velocity of the proximal joints at the concluding stages of the take-off could be attributed to a higher angular velocity of the distal joints, especially when the distal segments have not been rotated at the starting phases of the push-off (Bobbert & Van Soest, 2001). Furthermore, maximal jumps need a greater engagement of the hip extensor muscles at this point (Bobbert & Casius, 2005; Lees, Vanrenterghem, & De Clercq, 2004b) and when this is not feasible the larger effort could be achieved only by activating the calf muscles (Salles, Baltzopoulos, & Rittweger, 2011). The above mechanisms could interpret the larger extension of the hip joint at the instant of take-off on SAND, as well as the combined arm swing and surface effect which was detected for the hip joint range of motion. As found in a previous study (Giatsis et al., 2004), the larger mobility of the
hip joint is evident in vertical jumping on SAND, since the compliance of the sand resulted in a more flexed body configuration at the lowest position of the body in addition to the inability of the ankle joint to generate adequate propulsion. As for the AS effect, the larger hip joint range of motion is also proposed to be a result of the work generated at the shoulder joint, which results in the augmentation of the hip joint torque which eventually causes a higher JH (Cheng et al., 2008; Domire & Challis, 2010; Feltner et al., 1999, 2004; Hara et al., 2008).

Regarding the surface compliance, JH was smaller on SAND being in agreement with previous findings (Bisciotti et al., 2001; Bishop, 2003; Giatsis et al., 2004; Miyama & Nosaka, 2004; Muramatsu et al., 2006). This lower jumping performance could be attributed to the decreased force and power output values recorded for SAND compared to RIGID conditions, as generally observed in studies investigating jumping on sand surfaces (Bisciotti et al., 2001; Giatsis et al., 2004). A possible explanation could be the fact that sand is an inhibitory factor for the fast application of force (Bishop, 2003; Giatsis et al., 2004) which was especially noted for the NAS-CMJ in the present study. The combination of larger RFD and slower time to achieve maximum vertical GRF on SAND compared to RIGID tests leads to the suggestion that the sand was highly unstable. This was confirmed as the BCM take-off height referred to the initial standing position was significantly lower on SAND. The deformation of the sand is suggested to increase the demand for stability for the execution of jumping exercises (Binnie, Dawson, Pinnington, Landers, & Peeling, 2013c; Smith, 2006) as a result of the combined effect of the lower stiffness of the surface and its larger friction compared to sport surfaces (Bisciotti et al., 2001). It is also suggested that this demand for maintaining balance is causing increased work expenditure, since greater amounts of energy are absorbed during the interaction with the sand surface (Bisciotti et al., 2001; Bishop, 2003; Miyama & Nosaka, 2004; Muramatsu et al., 2006; Pinnington & Dawson, 2001) or the lower re-use of the stored elastic energy and the energy lost due to the slip of the feet backward (Impellizzeri et al., 2008).

The execution of the CMJ on SAND caused different body segment orientations for NAS and AS conditions. At the lowest vertical position of the BCM during the propulsive phase, the hip joint was more flexed at the NAS and more extended at the AS tests compared to the respective CMJs executed on RIGID. Moreover, the knee joint was more extended and the ankle joint was more flexed on SAND than on RIGID. Additionally, the inclination of the torso and the timing for its extension, which were found to be significant factors for jumping performance (Lees, Vanrenterghem, & De Clercq, 2006; Vanrenterghem, Lees, & Clercq, 2008), were different in each of the CMJ modalities tested in the present study. All the above could be an indirect indication of different muscle force-joint angle relationships of the knee and ankle extensor muscles during the downward phase. This has been thought to be a factor that determines jumping performance on SAND and which is strongly associated with the reduced muscle soreness after sand jumping training (Binnie, Dawson, Pinnington, Landers, & Peeling, 2013a; Binnie, Dawson, Arnot et al., 2014; Impellizzeri et al., 2008; Miyama & Nosaka, 2004; Mirzaei, Norasteh, Saez de Villarreal, & Asadi, 2014).

The unstable sand surface poses another discrepancy for the execution of the CMJ. Despite the fact that a higher activation of the knee extensor muscles is seen after sand CMJ training (Mirzaei, Norasteh, & Asadi, 2013), a decreased ability to efficiently coordinate the extension of the lower limb joints for the execution of a jumping task on SAND has been observed (Muramatsu et al., 2006; Smith, 2006). Previous researchers suggested that the execution of a stretch-shortening cycle action on SAND has a greater reliance on concentric muscle action, possibly due to the required compensation for the degradation of elastic energy due to sand instability (Binnie, Dawson, Pinnington et al., 2014; Impellizzeri et al., 2008).

When executing a running or sprinting action on a sand surface with high intensity, the patterns of joint movement are modified because of the interaction of the foot and the sand surface, especially the backward movement of the foot because of sand deformation at the end of the push off (Alcaraz, Palao, Elvira, & Linthorne, 2011; Gaudino et al., 2013; Impellizzeri et al., 2008). In order to resolve the problem of the unstable surface, a higher co-contraction is observed in lower limb muscles and thus a less optimum flow of energy (Gaudino et al., 2013). However, based on the curves presented in Figure 5, no differences of the pattern concerning the lower limb joints’ flexion/extension motion were observed. This could be attributed to the relatively longer duration of the impulse phase, during which the sand could have been compressed under the effect of the mass and the forces applied by the participants that eventually caused the sand surface to dissipate some of its absorptive qualities and thus it resembled a more rigid surface. It also might be the cause for the adjustments observed in the downward phase of the SAND-AS test, where peak angular velocity of the knee and the hip reached a lower value in a shorter time period. The above might indicate the major contribution of the joint flexor muscles that is necessary for the effective facilitation of the counter-movement (Nagano, Komura, Fukashiro, & Himeno, 2005), a fact that has to be further investigated on SAND countermovement jump.

With respect to beach volleyball skills, the use of an arm swing on a sand surface was associated with a larger forward inclination of the body at the lower position of the BCM. This should be in consideration for any vertical jump following an approach (i.e. spike or jump serve). Furthermore, at the end of the approach phase, in order to avoid the excessive backward movement of the feet at the end of the push-off, feet should be placed flat and not with a heel-toe or vice versa order. The examination of feet-surface interaction, especially on sand, only with kinematics retrieved from video analysis might pose a limitation concerning the understanding of the plantar flexion mechanics of pushing off against the deforming sand surface. Thus, future research should monitor the feet plantar flexion as it seems essential for interpreting the mechanics of jumping on sand.

As for training methods concerning jumping performance improvement, previous research suggested that training load can be increased by substituting common jumping surfaces with sand especially toward the end of preseason (Binnie,
Dawson, Pinnington, Landers, & Peeling, 2013b). Preseason training on a sand surface is proposed because of the decreased soreness, faster recovery and limited occurrence of overuse injuries (Binnie et al., 2013a; Binnie, Dawson, Arnott, et al., 2014; Gortsila et al., 2013). Greater training adaptations are expected over the preseason because heavier training loads can be applied (Binnie et al., 2013a; Impellizzeri et al., 2008). Additionally, the adaptations of jumping, sprinting and agility training on sand seem to be transferred on RIGID (Binnie, Dawson, Pinnington, et al., 2014; Gortsila et al., 2013). However, a relative short introduction period is necessary, because sand surfaces are less effective for inducing neuromuscular adaptations that are required for the improvement of high intensity due to the lower compliance of the sand that reduce the mechanical stimuli on the musculoskeletal system and thus limit the resultant training effects on the efficiency of the muscle-tendon complex (Binnie et al., 2013b; Binnie, Dawson, Pinnington, et al., 2014; Impellizzeri et al., 2008).

Countermovement jumping on sand, both with and without an arm swing, is a convenient to adopt training modality for beach-volleyball players, since almost similar patterns, compared to countermovement jumping on a rigid surface, are utilized. Additionally, the occurrence of a larger rate of force development is the advantage of executing countermovement jumping on sand, because fast adjustments must be made in order to execute the jumping pattern while the sand surface is deforming beneath the athlete. Based on these findings, countermovement jumps on sand aiming for maximal height are suggested as an alternative training modality for acquiring explosiveness in jumping drills. Finally, sand comprises a training surface for a faster extension of the ankle joint over a larger range of motion during the upward phase of the countermovement jump, because it causes the hip to extend in a larger magnitude in order to maintain the vertical movement of the body during the push-off. Thus, conditioning training programs on sand surfaces should include a substantial volume of strengthening the muscular system around the hip joint and the lower back.

**Conclusion**

Surface and arm swing effects were revealed for key force parameters that determine vertical jumping performance. The arm swing resulted in significant changes concerning the peak angular velocity of the examined lower extremity joints. Additionally, the CMJs executed on sand were characterized by significantly more flexed ankle joint and more extended knee joint at the lowest point of the BCM trajectory during the propulsion. A non-significant, yet larger angular velocity at the shoulder joint on sand, together with the differences observed for the body configuration at the transition from the downward to upward movement during the propulsion, possibly forced the muscles surrounding the hip joint to modify their function as compared to a CMJ executed on a rigid surface without the use of an arm swing.

Countermovement jumps executed on sand surface develop larger and stronger leg musculature and cause more energy to be spent per unit of time compared to a hard surface. Sand acts as resistance that provides longer time under tension to the muscles and involves more muscle fibers in order to jump, a precursor to muscle strength increase. Thus, executing preferably arm swing countermovement jumps on a sand surface benefits jumping performance by combining higher muscle activation and effective energy flow throughout the body during the impulse.

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**Disclosure statement**

No potential conflict of interest was reported by the authors.

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