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Article

Temporal analysis of cellular and molecular response-driven ground reaction forces in predicting volleyball spike jump height: Insight for optimizing spike jump performance

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Abstract: Ground reaction force (GRF) during jumping, which is an outcome of the complex cellular and molecular biomechanical processes within the lower limb, reflects the interaction of the lower limb with the ground. Previous studies, however, have been restricted to analyzing only the peak kinetics, overlooking the moment when the peak occurs and other essential details beyond the peak. Thus, the objective of our study was to explore the relationship between the full time series of GRF and jump height during volleyball spike jumps, considering the underlying cellular and molecular biomechanical mechanisms. Data on the kinematics and kinetics of 22 elite male (mean age: 21.56 years) collegiate volleyball players' spike jumps were gathered via a motion capture system comprising 13 high-speed cameras and 2 force plates. Then, we analyzed the association between the full ground reaction force time series and jump height using statistical parameter mapping (SPM) regression. The results of the study demonstrated that the horizontal GRF of the dominant foot was significantly related to jump height in the 23%–80% interval of dominant foot contact (DFC) with the force plate to take-off (TO). This association is likely due to the coordinated activation and contraction of specific muscle cells and molecular signaling pathways within the lower limb muscles that govern force generation and transmission. The vertical GRF of the dominant foot was significantly associated with jump height in the 29%–35% and 80%–94% intervals of DFC to TO, which could be attributed to the differential recruitment and activity of muscle fibers at the cellular and molecular levels. Similarly, the non-dominant foot was significantly associated with jump height in the 48%–63% interval of non-dominant foot contact (NFC) with the force plate to TO. These data emphasize the significance of enhancing lower limb muscle capacity through interventions that target the cellular and molecular biomechanical aspects, in order to improve jumping technique and overall performance.

Keywords: force-time; GRF; statistical parameter mapping; volleyball spike jumps; biomechanical processes

1. Introduction

Volleyball is widely popular worldwide as an Olympic sport. The spike is the most important offensive technique in volleyball and often determines the success of the match [1]. Theoretically the higher the offensive player jumps will get a larger effective spike area and a steeper spike line, which increases the difficulty for the opponent. Spike jump (SJ) height determines the performance of volleyball players and is therefore of great interest to coaches and sports scientists [2–5].

Common jumps (countermovement jumps (CMJ), Drop jumps (DJ)) are often used by coaches, trainers, or sports scientists to evaluate or predict volleyball players' jumping ability because these jumps use lower limb stretch-shortening cycles (SSC) [6,7]. But volleyball spiking jump action is more complex than general jump, athletes need 3–4 steps of horizontal acceleration before spiking jump, general jump test can't accurately predict jump height of volleyball spike [8–11]. One research shows that the horizontal acceleration force-velocity profile is positively correlated with the spike jump height [12]. Elite athletes are better at increasing jump height by increasing approach speed and stride length of the final planted leg [5,13,14]. Despite the important effect of horizontal acceleration on spike jumping highlighted in several studies, there is still a gap in relevant research on the relationship between horizontal GRF and jump height [5,12,15].

GRF reflects how the body interacts with the ground, and by extracting GRF parameters to find the best contributor to jump height, suggestions can be made to improve jump performance [16,17]. Previous studies of CMJ have shown that neither the relative nor absolute value of the vertical component of the peak has a significant relationship with jump height [18,19]. At the same time, Fuchs found that male and female elite volleyball players with significant difference jump height had no significant difference in vertical component peak value, but significant difference in horizontal component peak value during SJ [4]. The GRF is a continuous time series, and traditional analyses of peak GRF alone that do not consider when these peaks occur may not provide a full understanding of the GRF.

Statistical parametric mapping (SPM) is a research methodology applied in the field of neurology, based on the theory of random fields for statistical inference of normalized one-dimensional datasets [20,21]. The use of SPM analysis allows us to better understand the relationship between GRF and jump height during the entire volleyball spike jump, providing some insight into the development of training programs. Therefore, the purpose of this study was to describe the time-series characteristics of the GRF of male collegiate volleyball players during the spike jump and to establish a time-dependent link to jump height. We hypothesise that volleyball spike jump height is related to GRF, especially in the anterior-posterior and vertical directions.

2. Methods

2.1. Study design

Controlled laboratory study.

2.2. Participants

The experiment recruited 22 elite college volleyball players whose (mean age: 21.56 ± 2.32 years, mean height: 187.6 ± 3.37 cm, mean weight: 78.68 ± 6.4 kg, and mean: 9.67 ± 1.26 years of training). All participants had experience playing in the Korean Collegiate Volleyball League and had to be free of surgery and injury for a period of 6 months prior to the test. All subjects signed an informed consent form before the experiment, and the study was approved by the ethics committee of Jeonbuk

National University.

2.3. Data collection

All athletes were tested in the KyungHee University volleyball gym with equipment such as force plates and high-speed motion capture systems. 13 infrared cameras (Prime17w, OptiTrack, Natural Point, Inc, Corvallis, OR, USA) are used to record the coordinates of reflective markers on the participant's body at a sampling frequency of 240Hz. 2 force platforms (OR6-6-2000, AMTI, Inc, USA) record ground reaction forces during movement at a sampling frequency of 1200 Hz. Kinematic and kinetic data were synchronised by connecting the motion capture system device (OptiTrack, Natural Point, Inc., Corvallis, OR, USA).

The athletes first completed a standardized warm-up program including jogging, static and dynamic stretching, followed by a spiking exercise in which the athletes were required to use a straight line for 2–3 steps, depending on their spiking habits, until they could naturally place their feet on each of the two force plates. In addition, the volleyball is attached to a hanging device and the height of the volleyball can be adjusted according to the athlete's needs until the height of the volleyball is considered to be the most appropriate (**Figure 1**). The athlete then removed all loose clothing and placed reflective markers on 4 bony landmarks on the anterior and posterior superior iliac spine to calculate the position of the pelvic mass center. Once the markers had been placed, the athletes practiced their jumps again to fully acclimatise to the experimental environment. The test was initiated with the athlete's consent after all pre-laboratory preparations had been completed. The athlete first performs a static model acquisition in a natural standing position and then completes 5 successful trials, with a successful spike jump requiring both feet to be placed separately and completely on the force plate and the volleyball to be struck forcefully into a defined area. In order to prevent fatigue, the athletes have a 2-minute rest period after each jump. The best jump height from the 5 trials will be used for analysis.

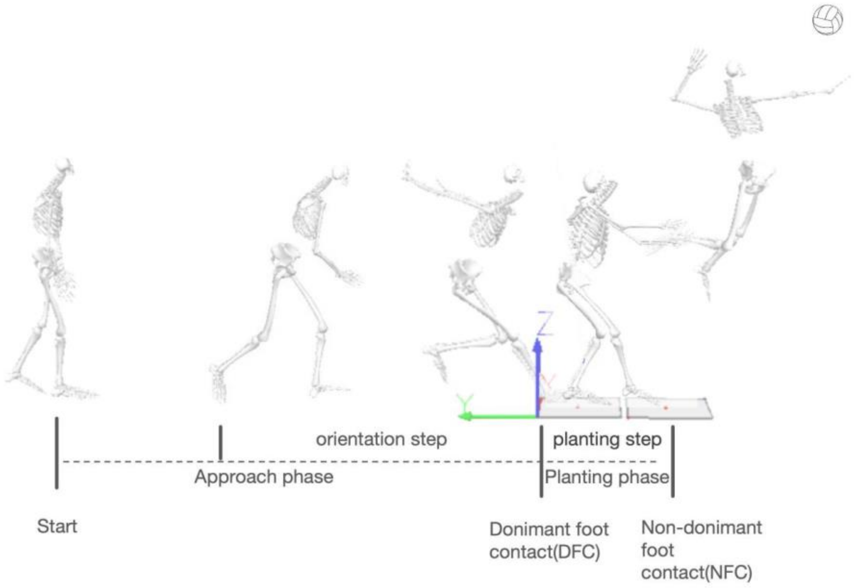

Figure 1. Experimental setup and phase division.

2.4. Data process

The most complete data with the highest jumps were included in the analysis, and the kinematic and kinetic data were analyzed in Visual3D software (C-Motion, Inc., Rockville, MD) and filtered using a Butterworth low-pass filter with cut-off frequencies of 40 Hz and 20 Hz, respectively. A laboratory coordinate system is set up in the Visual3D software, with the direction of the athlete's running and jumping as the Y axis, the vertical up as the Z axis, and the X axis perpendicular to the plane composed of the Y and Z axes (**Figure 1**). Create a CODA pelvis model in Visual3D software (Charnwood Dynamics Ltd, UK) and calculate the center of mass of the pelvis. The height of an athlete's jump is calculated from the difference between the height of the center of mass of the pelvis when standing and the height of the highest jump [22]. To calculate the temporal relationship between the GRF components and the height of the spike jump, we extracted the 3 components of the GRF for the dominant and non-dominant foot separately, where the GRF components for each foot were normalized to the foot contact force plate and the release force plate, with 0% for the dominant or non-dominant foot contacting the force plate and 100% for the release from the force plate. GRF components were analyzed after normalization for body mass to avoid the effect of body mass on spike jump height.

2.5. Statistical analysis

Both non-normalized and body-mass-normalized peak GRF as mean ± standard deviation was reported, but in order to reduce the effect of mass on jump height and GRF, only normalized GRF values were used in the statistical analyses. Statistical Parametric Mapping (SPM) was used to investigate the relationship between the components of the GRF and the height of the volleyball spike jump [23–25]. We constructed 6 univariate SPM regression models, each using spike jump height to predict the GRF component equation.

Equation (1).

$$Y = X\beta + \varepsilon \tag{1}$$

where Y is an $n \times 101$ matrix with each row corresponding to the time-normalized GRF signals of one athlete; X is an $n \times 2$ design matrix (with the first column containing 1 and the second column containing the athlete's matched jump height); β is a 2×101 matrix of regression coefficients (with columns 1 and 2 corresponding to the regression slopes and intercepts, respectively); and ε is an $n \times 101$ matrix of model residuals.

When SPM analyses showed significant associations between jump height and GRF components, we extracted β time series and calculated correlation coefficients and variance shares across time to more easily account for the polarity and strength of significant associations. We calculated correlation coefficients across time using the relationship between standardized and unstandardized regression coefficients in the single predictor regression equation.

Equation (2).

$$r_i = \beta_i \times \frac{sd_x}{sd_{y1}} \tag{2}$$

where r_i represents the correlation between jump height and GRF at time i, β_i represents the unstandardized SPM regression coefficient at time i (extracted from β in Equation (1)), sd_x represents the standard deviation of our sample of mean jump height, and sd_{yi} represents the standard deviation of the GRF signals at time i. The resulting values from Equation (2) were then squared to return the r^2 statistic (proportion of variance in GRF magnitude accounted for by jump height) over time.

We adjusted our a priori significance threshold to 0.008 using the Šidák correction for multiple comparisons, maintaining a family-wise error rate of 5% [26]. All analyses were performed in Python using the spm1d software package [27].

3. Results

The spike jump height for all subjects in our study was 67.29 ± 6.68 cm. SPM regression analyses showed that dominant leg horizontal force (GRF Y), vertical force (GRF Z) and non-dominant leg vertical force (GRF Z) were associated with spike jump height (**Figure 2**). Of these, the horizontal component accounted for between 23% and 80% of the time between dominant foot contact (DFC) with the force plate and take-off (TO) from the force plate (this time period is referred to as the region of significance), where an increase in jump height was associated with an increase in horizontal force (**Figure 2**). Within the region of significance, an increase in jump height of 1 cm was associated with an increase in horizontal force of 0.11 N/KG (**Figure 3**). This region can also explain 58.9% of the variance in jump height.

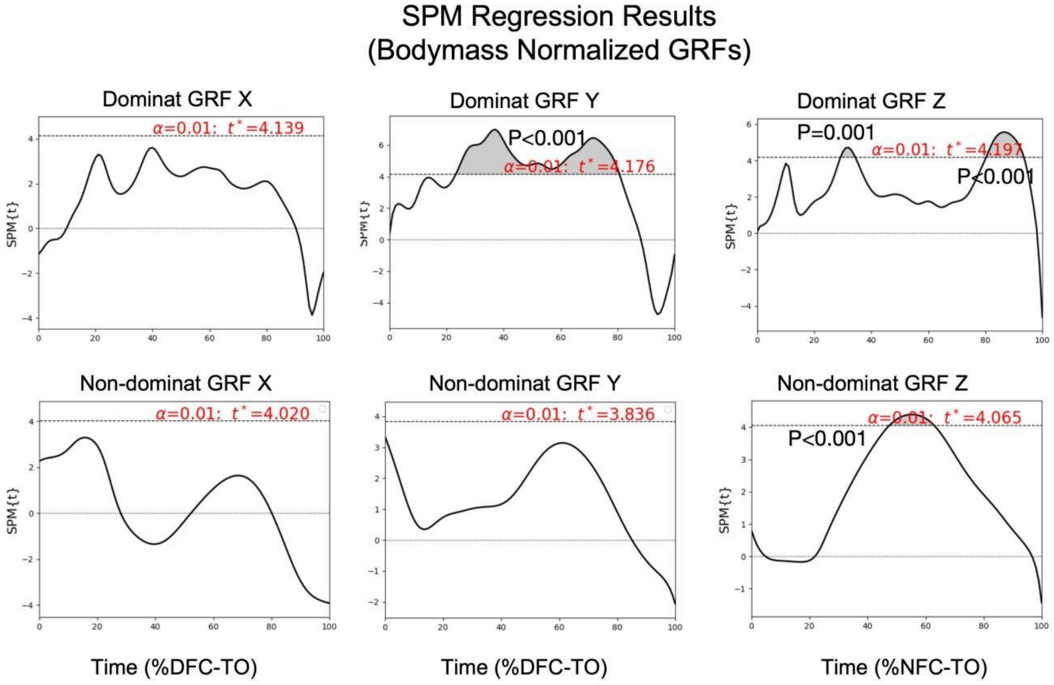

Figure 2. SPM regression results; spike jump height was associated with dominant foot GRF Y, GRF Z and non-dominant foot GRF Z. *X*-axis 0 represents the dominant foot contact (DFC) or non-dominant foot contact (NFC) with the force plate and 100 represents Take off (TO) form the force plate.

For the dominant foot vertical force, there are two moments in time between DFC and TO where jump height is correlated with vertical force, at 29%–35% and 80%–94% respectively (**Figure 2**). Within the 29%–35% significant region, an increase in jump height of 1 cm was associated with an increase in horizontal force of 0.23 N/KG; correspondingly, in the 80%–94% region, an increase in jump height of 1 cm is associated with an increase in vertical force of 0.32 N/KG. These two ranges explained 47% and 55% of the variance in jump height, respectively (**Figure 3**).

Finally, for the vertical force of the non-dominant foot, between 48% and 63% of the NFC to TO interval (**Figure 2**), a 1 cm increase in jump height was associated with a 0.33 N/KG increase in vertical force and explained 46.6% of the variance (**Figure 3**).

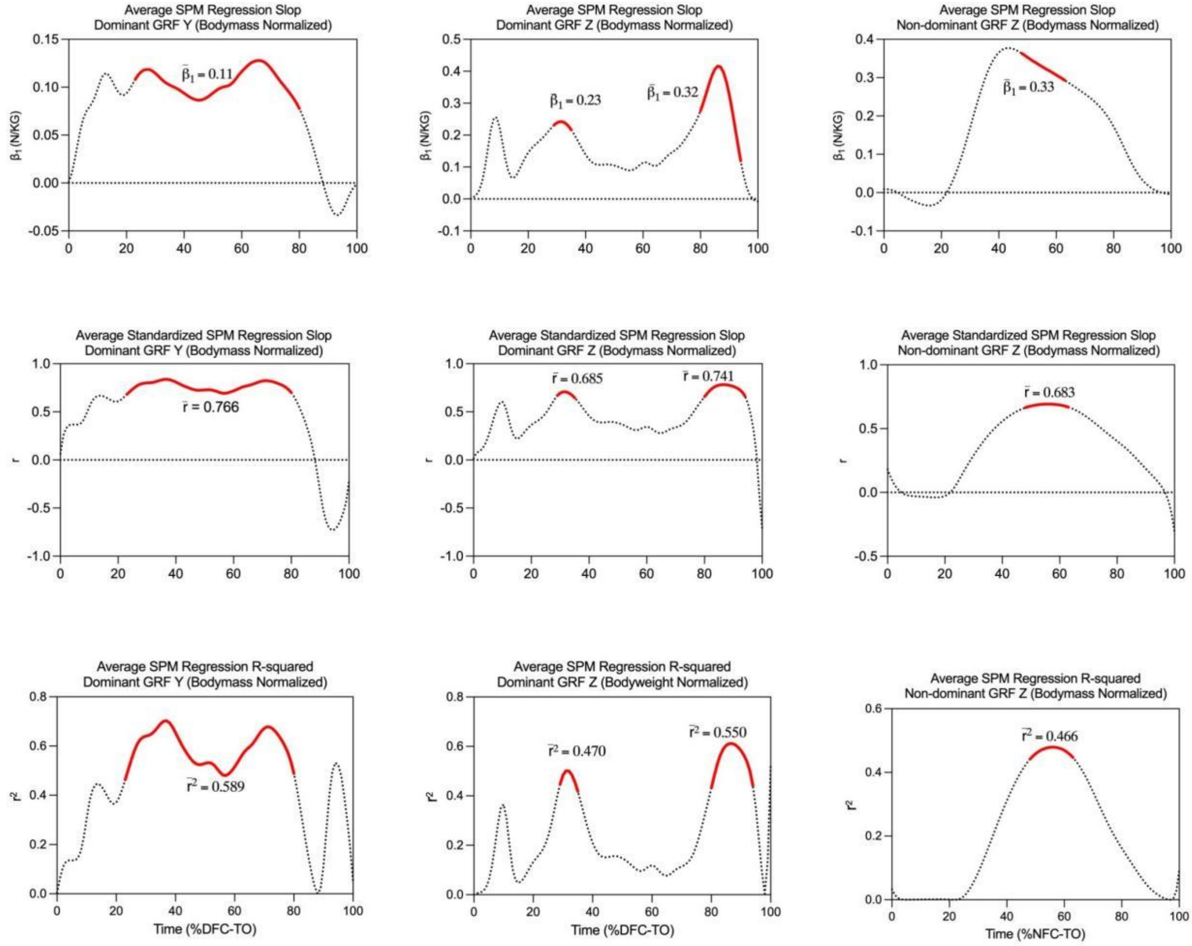

Figure 3. Regression slopes (top row), regression coefficients (middle row) and *R*-squared (bottom row) for SPM over time. The dashed lines indicate the regression model slope (top row), the standardized regression model slope (middle row) and the proportion of the change in GRF accounted for by the height of the jump (bottom row) at each time point, respectively. Regions where the jump height is significantly correlated with the corresponding GRF are highlighted in red. *X*-axis 0 represents the dominant foot contact (DFC) or non-dominant foot contact (NFC) with the force plate and 100 represents Take off (TO) form the force plate.

Table 1. Non-normalized and Body-mass-normalized two-leg peak ground reaction Forces. The horizontal GRF (Y) is perpendicular to the net towards the back of the athlete, the vertical GRF (Z) is perpendicular to the ground upwards, and the Medial/Lateral GRF (X) are perpendicular to the plane made up of the *Y* and *Z* axes.

	Mean ± SD (*N*)	**Mean ± SD (N/KG)**
Dominant Leg		
Horizontal	305.82 ± 101.52	3.87 ± 1.16
Medial/Lateral	86.32 ± 53.41	1.08 ± 0.63
Vertical	1434.02 ± 204.77	18.25 ± 2.06
Non-dominant Leg		
Horizontal	697.55 ± 94.84	8.88 ± 1.00
Medial/Lateral	171.16 ± 61.07	2.17 ± 0.77
Vertical	2094.83 ± 392.27	26.54 ± 3.59

Mean ± SD represents the mean and standard deviation of the Non-normalization and Body-mass-normalized ground reaction forces. The second column is for non-normalization ground reaction forces and the third is for Body-mass-normalized ground reaction forces. explanations of the acronyms in **Table 1**.

4. Discussion

The present study analyzed the relationship between volleyball spike jump height and GRF using a full time series via SPM. The results of the study showed that the horizontal braking force after contact of the dominant foot with the ground and the partial vertical force of both feet were closely related to the jump height after controlling for body mass. The results are consistent with previous studies and reiterate that improving the lower limb muscle stretch-shortening capacity and spike-jumping technique can improve spike jump height [4,5,28–30].

The present study analyzed full time series description of the GRF of both feet during the spike jump and listed the peak non-normalized and mass-normalized values of the GRF components, with jump heights and GRFs close to those of the elite volleyball players in the study by Philip X. Fuchs (**Table 1**, **Figure 4, Figure 5**) [4].

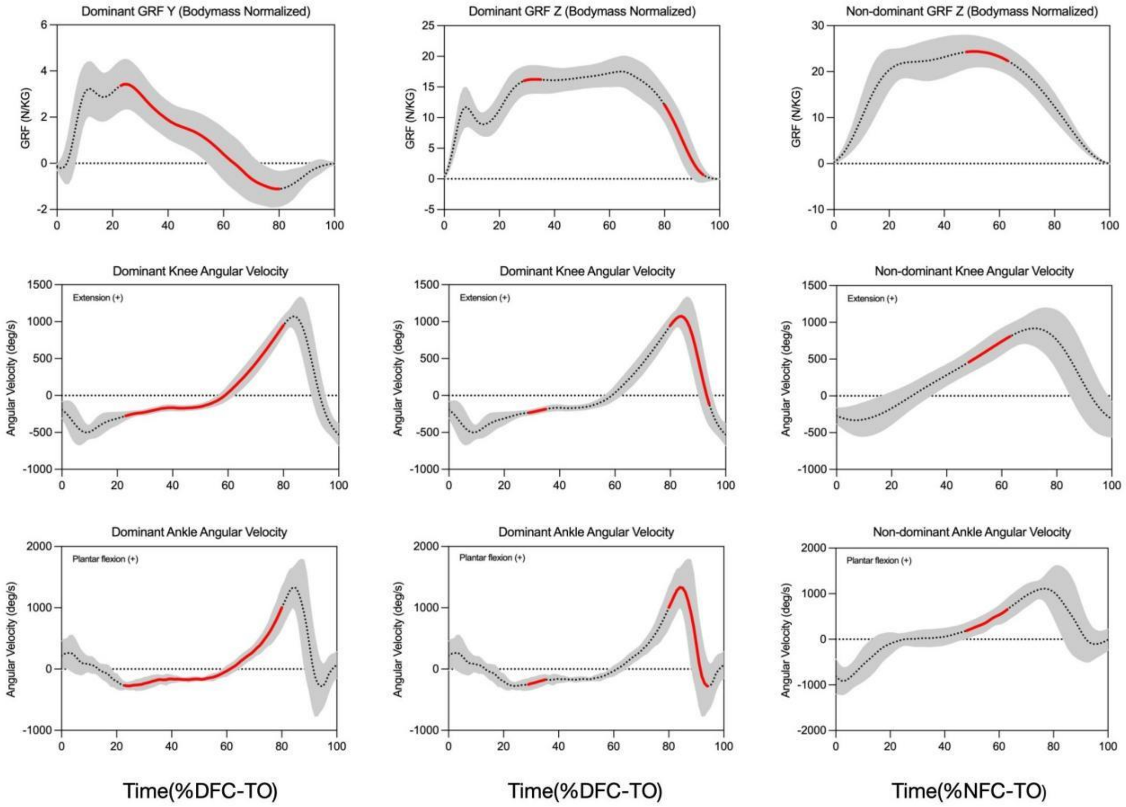

Figure 4. Time series of the GRF, with periods where the jump height is significantly correlated with the GRF marked in red (top row). Time series of knee (middle row) and ankle (lower row) angular velocities with intervals based on jump height significantly correlated with GRF highlighted in red. The dashed line represents the mean for all participants and the shaded area represents the standard deviation. X-axis 0 represents the dominant foot contact (DFC) or non-dominant foot contact (NFC) with the force plate and 100 represents Take off (TO) form the force plate.

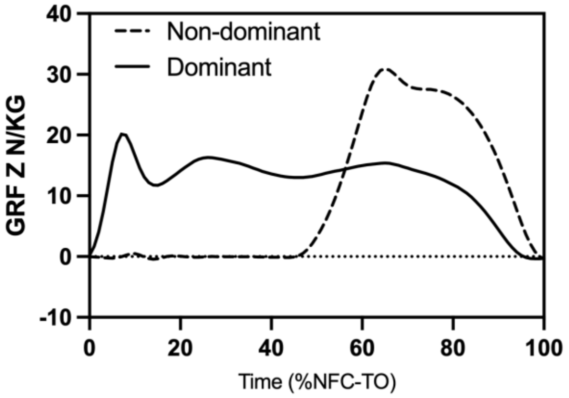

Figure 5. Time series of vertical components of GRF in the dominant and non-dominant feet of a typical subject. X-axis 0 represents the dominant foot contact (DFC) or non-dominant foot contact (NFC) with the force plate and 100 represents Take off (TO) form the force plate.

4.1. Temporal correlation between jump height and horizontal GRFs

The main aim of the present study was to investigate the relationship between GRF properties throughout the entire spike-jump cycle and jump height. It was hypothesized that horizontal GRF would be significantly associated with jump height, and the results of the study supported the hypothesis. Specifically, horizontal GRF in the dominant foot was significantly correlated with jump height for 23%–80% of the time period from DFC to TO, and a 1 cm increase in jump height implied a corresponding 0.11 N/KG increase in horizontal force, corresponding to an 8.7 N increase in horizontal force for our subject's average body mass of 78.7 kg.

From the dominant foot GRF-Y, the region of significant correlation begins at 23% of the jump cycle, approximately at the second GRF peak, when the dominant leg knee is under centrifugal control and the lower limb muscles are fully activated and storing energy in the muscle tendons (**Figure 4**) [31,32]. Previous studies have shown that plyometric training and increased centrifugal phase loading to improve lower limb centrifugal control can improve spike jump performance, which is consistent with our findings [33–35]. Around 60% of the jump cycle the knee begins to contract centripetally and the horizontal force changes from a braking force to a propulsive force at this point until the peak knee extension angular velocity (80% of the jump cycle), where any increase in horizontal force has a positive effect on jump height. In summary, in the planting phase after the acceleration phase, it is more effective for athletes to use the dominant foot to decelerate the body (**Figure 1**). The reason for this is that early deceleration of the dominant foot can store energy in the muscular tendons and at the same time reduce the distance between the feet so that the center of gravity of the body is closer to the feet and the vertical force can effectively propel the body upwards to accelerate [4].

Several studies have shown that increasing the horizontal speed of the approach phase, increasing the length of the stride and decreasing the planting of the dominant leg facilitate improved jumping technique to increase the height of the volleyball spike jump [4,5,14]. By improving lower body muscular capacity and jumping technique, the dominant foot's horizontal GRF can be increased, ultimately increasing spike jump height.

4.2. Temporal correlation between jump height and vertical GRFs

The vertical GRF of the dominant foot appeared to be significantly correlated with jump height for two time periods, with the first significant correlation occurring around 23% of DFC to TO, when the knee is centrifugally controlled and the GRF reaches its second peak moment. The volleyball spike jumps bilaterally with asymmetry, the dominant leg first flexes quickly after landing and then the knee joint under the control of the knee extensors gradually slows down the angular velocity of flexion, the activation of the dominant leg muscles increased with increasing approach velocity, which in turn increased lower limb stiffness and led to increased pre-landing stretch velocity, improved stretch reflexes, elastic energy storage and reuse, and thus increased vertical GRF (**Figure 4**) [36–39].

The second significant region occurs near the maximum knee extension angular velocity and almost overlaps with the vertical GRF of the non-dominant foot (**Figure 4**). Using the average body mass of 78.7 kg for all samples in this study, a 1 cm increase in jump height was associated with 18.1 N and 25.2 N increases in vertical GRF over the two periods, respectively. For the non-dominant foot, the 48%–63% peak moments from NFC to TO were significantly correlated with jump height, with a vertical force of 26 N required to increase jump height by 1 cm. The true vertical force, which determines the height of the jump, occurs about 80% of the jump cycle when the knee and ankle angular velocity of the dominant leg reaches a maximum, as the ankle contributes as much to the jump as the knee [40]. In addition, the vertical GRF of the non-dominant leg is also at its maximum at this moment, as the legs work together to propel the body's center of mass upwards.

The practical significance of this study lies in the fact that the relationship between GRF of the feet and jump height during volleyball dunking jumps has been explored in depth using time series analysis, emphasizing the importance of improving the extension-shortening capacity of the lower limb muscles and jumping technique. This provides the basis for coaches and athletes to develop more targeted training programmers to optimize performance. In addition, the innovation in research methodology provides new perspectives for future correlation studies, which in turn will advance the development of sport science.

4.3. Limitations and future study

Our findings should be viewed with caution, as all subjects were attempting to spike a stationary volleyball, which differs from a real game where athletes have to adjust their jumps according to the setter's passes, which may lead to discrepancies with laboratory data. Secondly, the purpose of our study was only to examine the relationship between GRF and spike jump height, and we were unable to establish the causal relationship between them, let alone examine changes over time.

Future studies should further explore the effects of increased lower limb strength and improved jumping technique on GRF and jump height. In addition, it would be useful to analyze the parameters of the spike jump for each volleyball position separately, as the attacking tasks and playing conditions of the attackers are different for different positions.

5. Conclusions

Our study was the first to examine the full time series relationship between ground reaction force during spike jumps and jump height in elite college volleyball players. The results of the study confirmed our hypothesis that the horizontal ground reaction force of the dominant leg and the partial vertical ground reaction force of both feet are associated with volleyball spike jump height. The relationship between ground reaction forces and jump height further supports the need to improve lower body strength training and jumping technique to improve jump performance.

Author contributions: Conceptualization, MD, JW and BL; methodology, MD, JW and SK; software, MD, JW and WG; validation, YK, SK and BL; formal analysis, MD, BL and WG; investigation, MD, WG, YK and BL; resources, JW and YK; data curation, MD and BL; writing—original draft preparation, MD and BL; writing—review and editing, JW and SK; visualization, SK; supervision, SK; project administration, JW; funding acquisition, BL. All authors have read and agreed to the published version of the manuscript.

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Ethical approval: The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Jeonbuk National University (JBNU2022-01-004-002, approved on 1 April 2022). All subjects signed an informed consent form before the experiment.

Conflict of interest: The authors declare no conflict of interest.

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