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## Feasibility of a Markerless Motion Capture System for Estimating Ground Reaction Forces During Vertical Jump and Landing Tasks

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## **Abstract**

**Background:** Vertical ground reaction force is an important kinetic variable for evaluating the biomechanical characteristics of vertical jump and landing tasks and is widely used in performance assessment and injury-risk screening.

**Aim:** To investigate the feasibility of the OpenCap markerless motion capture system for estimating vertical GRF during vertical jump and landing tasks.

**Material and methods:** Eighteen physical education students participated in this study. Kinematic data were collected using OpenCap, and vertical GRF was estimated from whole-body center-of-mass acceleration based on Newton's second law. Estimated GRF was compared with force plate measurements. Phase duration, peak force, mean force, and impulse variables were extracted. Pearson correlation and Bland-Altman analyses were used to assess validity.

**Results:** Strong correlations were observed between OpenCap-estimated and force plate-measured GRF variables. Temporal, impulse, and mean force variables showed moderate-to-very high correlations ( $r = 0.62-0.94$ ). Bland-Altman analysis indicated biases below 5% for temporal and impulse variables, while biases for propulsive-phase mean and peak force ranged from 5% to 15%. However, peak landing force showed a bias exceeding 40%, indicating substantial underestimation.

**Conclusions:** OpenCap provides a feasible method for estimating vertical GRF during vertical jump and landing tasks and may support large-scale movement assessment. However, peak landing force is substantially underestimated and should be interpreted with caution.

**Keywords:** OpenCap; markerless motion capture; ground reaction force; vertical jump; landing

## 1. Introduction

Performance assessment plays a critical role in sports training, physical fitness monitoring, and motor function evaluation (Thornton et al., 2019). Among the various movement tasks used for performance evaluation, jumping is one of the most commonly adopted assessments because it provides comprehensive insights into an individual's lower-limb force-generating capacity and neuromuscular control (Ishikawa & Komi, 2004; Markovic et al., 2004). Vertical jumping and landing are fundamental movement skills that underpin more complex athletic actions performed in sports such as basketball, volleyball, and track and field (Ryan et al., 2006).

During vertical jumping and landing, vertical ground reaction force (GRF) is an important kinetic parameter that reflects the dynamic characteristics of human movement (Niu et al., 2014). Therefore, accurately obtaining vertical GRF is essential for evaluating movement quality and developing effective training interventions (Halson, 2014; Thorpe et al., 2017). Currently, three-dimensional force plates can record kinetic changes during human movement with high precision and are widely regarded as the gold standard for GRF measurement (Mylonas et al., 2023). However, their high cost and laboratory-dependent setup substantially limit their application in large-scale physical fitness monitoring and routine educational or training settings (FENG Ru et al., 2021). In recent years, advances in computer vision, deep learning, and markerless motion capture technologies have enabled researchers to obtain human kinematic parameters from video recordings and estimate kinetic variables by integrating biomechanical models (Bobbert et al., 1991; Peng et al., 2024). OpenCap, a markerless motion capture system developed by Stanford University, utilizes smartphone videos in combination with pose-estimation algorithms, deep learning models, and the OpenSim musculoskeletal modeling framework to reconstruct three-dimensional human movement and calculate biomechanical variables (Uhrich et al., 2023). Compared with traditional laboratory-based equipment, OpenCap offers several advantages, including lower cost, greater deployment flexibility, and reduced environmental requirements.

Previous studies have shown that OpenCap can provide valid kinematic measurements during a range of functional movements, including gait, squatting, and running (Cheng et al., 2025; Lima et al., 2024). Furthermore, OpenCap-derived kinematic data have recently been used to estimate vertical GRF during jumping tasks (Verheul et al., 2024; You et al., 2026). Despite these promising findings, evidence regarding the validity of OpenCap-based GRF

estimation during vertical jumping and landing remains limited. Whether the kinematic information obtained from OpenCap can reliably support the estimation of vertical GRF throughout both the take-off and landing phases has yet to be systematically investigated. Therefore, the purpose of this study was to evaluate the feasibility of estimating vertical GRF during vertical jumping and landing using OpenCap. Specifically, kinematic data were collected using the OpenCap markerless motion capture system, and vertical GRF was estimated from whole-body center-of-mass acceleration based on Newtonian mechanics. Force plate measurements were used as the gold-standard reference to assess the correlation and agreement between the GRF variables derived from the two methods. Unlike our previous study conducted in preschool children (You et al., 2026), the present study systematically evaluated the feasibility of using OpenCap to estimate vertical GRF during vertical jump and landing tasks in undergraduate students majoring in physical education. In addition to examining GRF characteristics during jumping and landing, this study further investigated landing stabilization kinetics, which are closely related to athletic performance assessment and injury-risk screening. Therefore, the present study not only verified the applicability of OpenCap in a university student population, but also extended its application to adult vertical jump and landing tasks, providing further support for the application of OpenCap in performance monitoring, movement quality assessment, and injury-risk screening.

## **2. Research materials and methods**

### **2.1 Participants**

A total of 18 undergraduate students majoring in Physical Education from Southwest University, Chongqing, China, participated in this study, including 9 males and 9 females. Inclusion criteria: participants were physically healthy and had normal cognitive and motor function. Exclusion criteria: participants with any injury or disease affecting lower-limb movement at the time of testing were excluded from the study.

### **2.2 Instrumentation**

A portable force plate (Kistler 9260AA, Winterthur, Switzerland) was used as the gold-standard reference to record the kinetic characteristics of the jumping and landing tasks. Ground reaction force data were collected at 1000 Hz using Kistler BioWare software (version 5.5.1.0) (Verheul et al., 2024). Markerless motion capture data were acquired using two iOS devices (iPhone 12, Apple Inc., Cupertino, CA, USA) running the OpenCap application (Model Health

Inc., Stanford University, USA). The two cameras were positioned approximately  $\pm 40^\circ$  relative to the direction of movement and at least 4 m from the testing area to minimize occlusion and ensure full coverage of the movement space (Uhlrich et al., 2023). Kinematic data were collected at a sampling frequency of 120 Hz (Verheul et al., 2024).

### **2.3 Experimental Procedure**

All participants wore tight-fitting athletic clothing provided by the laboratory. Before testing, participants completed a standardized warm-up and several practice trials to familiarize themselves with the experimental procedures. Force plate data acquisition was initiated at 1000 Hz before each trial. For the vertical jump task, participants stood quietly in the center of the force plate with their feet shoulder-width apart for 3 s. Following a verbal command, kinematic recording commenced and participants performed a maximal vertical jump. For the landing task, participants stood on a 30-cm platform with their hands placed on their hips. After the verbal command, kinematic recording was initiated. Participants stepped forward with their dominant leg, followed immediately by the contralateral leg, and then dropped naturally onto the force plate, landing with both feet simultaneously. Participants were instructed to minimize horizontal velocity during the descent. After landing, they remained standing quietly on the force plate for 3 s before stepping off. A trial was considered valid when the participant completed the task successfully according to the experimental requirements. Each participant performed three successful trials for each task. To minimize the effects of fatigue, a rest interval of at least 1 min was provided between consecutive trials. All testing procedures were conducted indoors in a spacious laboratory environment with stable lighting conditions.

### **2.4 Phase Definition**

For the vertical jump task, four events were identified from the vertical GRF signal: propulsion onset, take-off, landing, and stabilization. Propulsion onset was defined as the first instant at which the vertical GRF exceeded BW following the countermovement phase. Take-off was defined as the first instant at which the vertical GRF fell below 5% BW and remained below this threshold. Landing was defined as the first instant after flight at which the vertical GRF exceeded 5% BW and remained above this threshold. Stabilization was defined as the point at which the vertical GRF returned to within  $\pm 5\%$  BW and remained stable for at least 0.1 s. Based on these events, three phases were identified: the propulsive phase (propulsion onset to take-off), the flight phase (take-off to landing), and the landing stabilization phase (landing to stabilization). For the landing task, the landing and stabilization events were identified using

the same criteria, and the interval between these two events was defined as the landing stabilization phase.

## 2.5 Calculation of Vertical Ground Reaction Force from Kinematic Data

The vertical GRF during the tasks was estimated from whole-body kinematic data by calculating the velocity of the body center of mass and applying Newton's second law. Data processing was performed using the OpenCap-processing library ([github.com/opencap-org/opencap-processing](https://github.com/opencap-org/opencap-processing)), which is based on the OpenSim musculoskeletal modeling framework. The model consists of 22 body segments, each of which is assigned specific mass properties and a corresponding local center-of-mass location.

(1) At any time point  $t$ , the whole-body center of mass (CoM) position was calculated as the mass-weighted average of the segmental centers of mass. Specifically,  $m_i$  and  $r_i(t)$  represent the mass and center-of-mass position of the  $i$ -th body segment, respectively, and  $N$  denotes the total number of body segments.

$$r_{COM}(t) = \frac{1}{\sum_{i=1}^N m_i} \sum_{i=1}^N m_i r_i(t) \quad (1)$$

(2) The vertical acceleration of the whole-body center of mass was obtained by numerically differentiating the vertical displacement of the CoM with respect to time.

$$a_{COM}(t) = \frac{d^2 r_{COM}(t)}{dt^2} \quad (2)$$

(3) On this basis, according to Newton's second law, the vertical GRF was derived from the vertical acceleration of the whole-body CoM, where  $m$  is the participant's total body mass and  $g$  is the gravitational acceleration ( $9.81 \text{ m} \cdot \text{s}^{-2}$ ).

$$F_{GRF} = m(a_{COM} + g) \quad (3)$$

(4) To facilitate inter-participant comparisons, the estimated vertical GRF values were normalized to body weight ( $BW = m \times g$ ), where  $m$  represents body mass and  $g$  represents gravitational acceleration, and were expressed as multiples of body weight.

$$vGRF_{BW} = \frac{a_{COM} + g}{g} \quad (4)$$

Following GRF estimation, the resulting kinetic data were processed in Python. The estimated vertical GRF signals were first filtered using a second-order low-pass Butterworth filter with a cut-off frequency of 4 Hz (Verheul et al., 2024). To ensure temporal consistency

and enable direct comparison with force plate data, the filtered GRF signals were subsequently resampled to 1000 Hz using linear interpolation (Xu et al., 2025).

## **2.6 Outcome Measures**

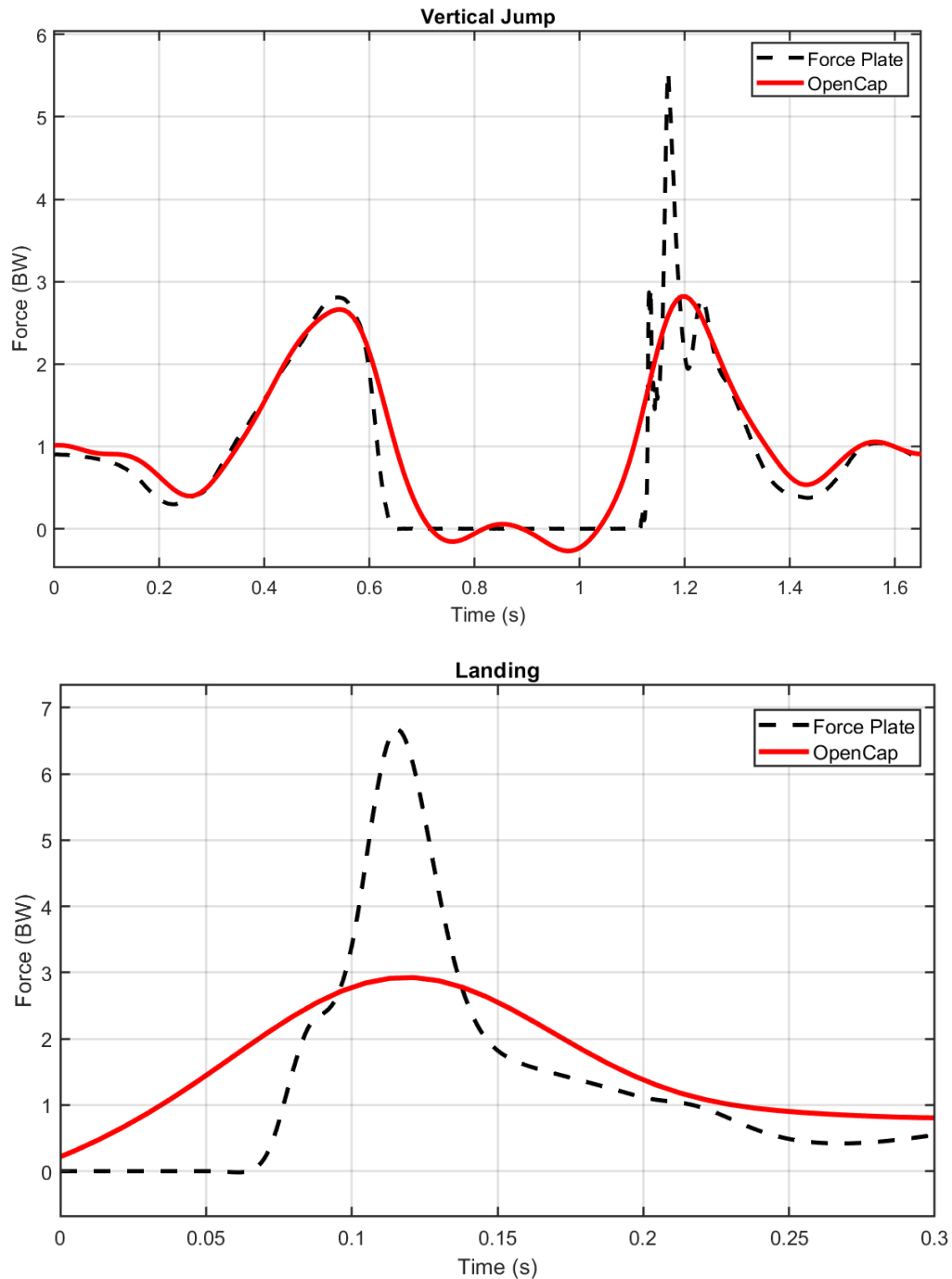
For the vertical jump task, the duration of the propulsive phase, flight phase, and landing stabilization phase were assessed. In addition, the peak force, mean force, and impulse during both the propulsive phase and landing stabilization phase were calculated. For the landing task, the duration of the landing stabilization phase, as well as the peak force, mean force, and impulse during this phase, were evaluated.

## **2.7 Statistical Analysis**

Statistical analyses were performed using SPSS Statistics 27.0 (IBM Corp., Armonk, NY, USA). All variables are presented as mean  $\pm$  standard deviation (Mean  $\pm$  SD). Descriptive statistics were used to summarize the mean and standard deviation of each variable. Pearson correlation analysis was conducted to examine the relationships between the force plate measurements and the OpenCap-estimated values. Statistical significance was set at  $P < 0.05$ . In addition, MATLAB (version R2024b, MathWorks, Natick, MA, USA) was used to calculate the relative estimation bias and generate graphical visualizations to assess the agreement between force plate measurements and OpenCap estimates. Smaller absolute values of relative estimation bias indicate better agreement between the measured and estimated values (Huang et al., 2025).

## **3. Research results**

A total of 108 trials were collected and processed, including 54 vertical jump trials and 54 landing trials. All participants completed the required movements under the guidance of the investigators. Figure 1 shows representative vertical GRF curves obtained from force plate measurements and OpenCap estimates during the vertical jump task.



**Figure 1.** Representative measured (black dashed line) and estimated (red solid line) ground reaction forces during the vertical jump and landing.

Table 1 summarizes the means, standard deviations, and Pearson correlation coefficients of the vertical GRF variables obtained from force plate measurements and OpenCap estimations during the vertical jump and landing tasks. The results showed that the vertical GRF variables estimated by OpenCap were highly correlated with the measured values across different movement phases. High correlations were observed for phase duration variables ( $r=0.86-0.94$ ), impulse variables ( $r=0.77-0.94$ ), and mean force variables ( $r=0.62-0.73$ ). In contrast, the

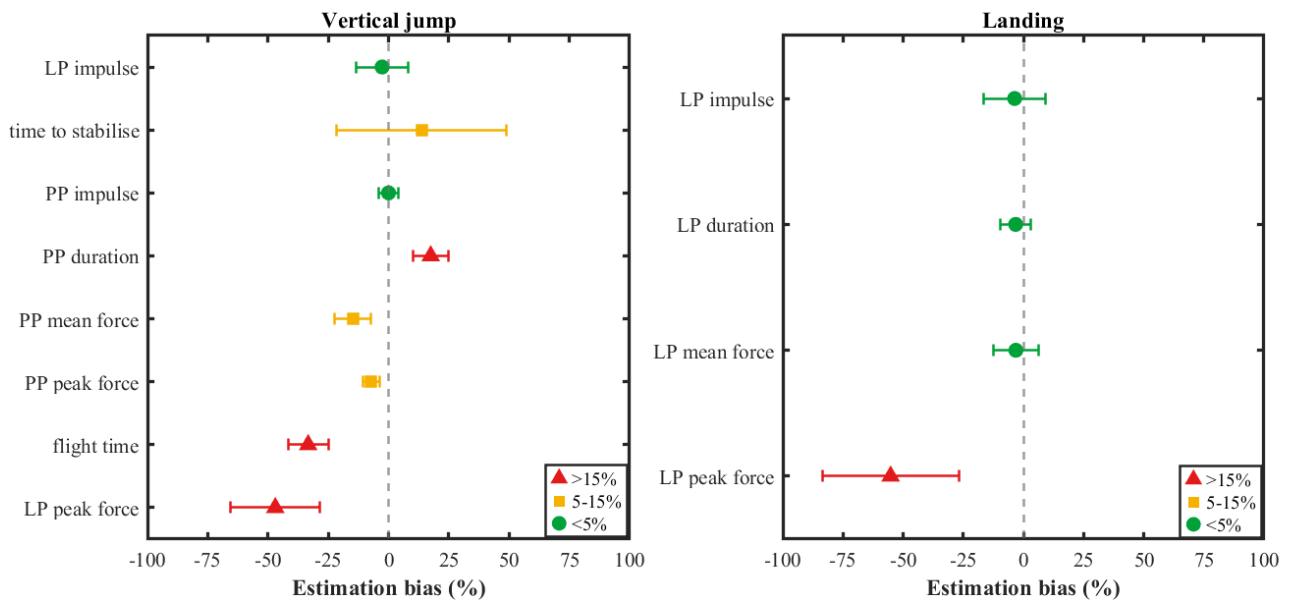
correlations for peak force variables varied considerably across phases. Peak force during the propulsive phase demonstrated a high correlation ( $r=0.84$ ), whereas peak force during the landing stabilization phase showed only moderate correlations ( $r=0.62-0.64$ ).

**Table 1.** Descriptive statistics and Pearson correlation coefficients for measured and estimated ground reaction force variables during the vertical jump and landing tasks.

Variable	Measured	Estimated	Difference	r	ICC (2,1)
<b>Vertical Jump</b>					
Flight phase duration (s)	$0.48 \pm 0.05$	$0.32 \pm 0.06$	$0.16 \pm 0.04$	0.86	0.82
Landing stabilization phase duration (s)	$0.51 \pm 0.17$	$0.58 \pm 0.19$	$-0.07 \pm 0.18$	0.91	0.87
Mean force during the propulsive phase (BW)	$1.82 \pm 0.18$	$1.55 \pm 0.16$	$0.27 \pm 0.14$	0.73	0.71
Mean impulse during the landing stabilization phase (BW·s)	$0.75 \pm 0.17$	$0.73 \pm 0.15$	$0.02 \pm 0.08$	0.87	0.86
Mean impulse during the propulsive phase (BW·s)	$0.72 \pm 0.10$	$0.73 \pm 0.09$	$0.00 \pm 0.03$	0.94	0.93
Peak force during the landing stabilization phase (BW)	$4.98 \pm 1.08$	$2.63 \pm 0.30$	$2.34 \pm 0.92$	0.62	0.28
Peak force during the propulsive phase (BW)	$2.52 \pm 0.26$	$2.33 \pm 0.23$	$0.18 \pm 0.09$	0.84	0.85
Propulsive phase duration (s)	$0.40 \pm 0.08$	$0.47 \pm 0.08$	$-0.07 \pm 0.03$	0.94	0.86
<b>Landing</b>					
Mean force during the landing stabilization phase (BW)	$1.60 \pm 0.11$	$1.56 \pm 0.16$	$0.05 \pm 0.15$	0.62	0.79
Mean impulse during the landing stabilization phase (BW·s)	$0.55 \pm 0.07$	$0.53 \pm 0.07$	$0.02 \pm 0.07$	0.81	0.76
Peak force during the landing stabilization phase (BW)	$6.36 \pm 1.98$	$2.86 \pm 0.29$	$3.51 \pm 1.81$	0.64	0.24
Landing stabilization phase duration (s)	$0.62 \pm 0.12$	$0.60 \pm 0.08$	$0.02 \pm 0.04$	0.91	0.83

**Note:** BW = body weight; ICC = intraclass correlation coefficient.

Figure 2 presents the agreement between force plate measurements and OpenCap-estimated vertical GRF variables during the vertical jump and landing tasks, as assessed using Bland-Altman analysis. The results showed that the agreement bias for propulsive phase duration, landing stabilization phase duration, and landing-phase impulse was within  $\pm 5\%$ . The agreement bias for peak force during the propulsive phase, mean force during the propulsive phase, and impulse during the propulsive phase ranged from  $-5\%$  to  $-15\%$ , indicating acceptable levels of agreement between the measured and estimated values. In contrast, the agreement bias for peak force during the landing phase exceeded  $40\%$ , suggesting that OpenCap substantially underestimated peak landing forces compared with force plate measurements.



**Figure 2.** Percentage bias and limits of agreement between the measured and estimated vertical ground reaction force variables for the vertical jump and landing. Circles/green, squares/amber, and triangles/red represent a bias/limit of agreement of  $<5\%$ ,  $5-15\%$ , or  $>15\%$ . LP = landing phase, PP = propulsive phase method.

#### 4. Discussion

The present study used the OpenCap markerless motion capture system to obtain kinematic data and estimate vertical GRF based on whole-body center-of-mass dynamics during vertical jump and landing tasks. The estimated GRF values were compared with force plate measurements to evaluate their correlation and agreement. The GRF variables analyzed in this study are commonly used in assessments of athletic performance and injury-risk screening. The

correlation analysis demonstrated that OpenCap-estimated vertical GRF showed high correlations with force plate measurements for phase duration and impulse-related variables across different movement phases ( $r = 0.81-0.94$ ). These findings are consistent with those reported by Verheul et al. (Verheul et al., 2024), who observed correlations ranging from 0.90 to 0.99 when using OpenCap to estimate GRF variables during jumping tasks. Agreement analysis further indicated moderate-to-very high agreement between OpenCap estimates and force plate measurements across most GRF variables obtained during the vertical jump and landing tasks. In particular, impulse-related variables exhibited relative biases of less than 5%, indicating excellent agreement. In addition, the relative biases for peak force and mean force during the propulsive phase ranged from 5% to 15%. Previous studies have generally considered a relative bias of less than 15% to indicate acceptable estimation accuracy (Martin Bland & Altman, 1986; Verheul et al., 2024). These findings suggest that GRF estimated using the OpenCap markerless motion capture system can accurately characterize the kinetic characteristics of vertical jump and landing movements. Among all variables examined, the highest estimation accuracy was observed for variables associated with the propulsive phase of the vertical jump. Therefore, OpenCap-based GRF estimation may provide a practical alternative for obtaining vertical GRF data outside laboratory environments and has considerable potential for applications in training monitoring, physical performance assessment, and long-term athlete tracking. Nevertheless, several variables demonstrated lower estimation accuracy. Specifically, peak force during the landing task and the landing stabilization phase of the vertical jump exhibited relatively low correlations ( $r = 0.62-0.64$ ), with relative biases exceeding 40%. In addition, the relative bias for flight-phase duration exceeded 15%. Compared with force plate measurements, OpenCap systematically underestimated both landing peak forces and flight-phase duration. One possible explanation for these discrepancies is the difference in sampling frequency between the two measurement systems. The force plate recorded data at 1000 Hz, whereas OpenCap collected kinematic data at 120 Hz. Peak landing forces typically occur within a very short time interval and are characterized by rapid changes in velocity and loading. Such transient impact events are difficult to capture accurately using lower-frequency video-based motion capture systems (Verheul et al., 2024). Furthermore, the center-of-mass acceleration used for GRF estimation is derived from filtered kinematic data. A relatively low cut-off frequency (4 Hz) was selected to reduce noise amplification caused by numerical differentiation of center-of-mass displacement. However, such filtering may also attenuate high-frequency impact components during landing, resulting in underestimation of peak landing forces and

inaccuracies in flight-phase duration estimation (Verheul et al., 2024). Therefore, although OpenCap demonstrates promising performance for estimating low-frequency GRF characteristics such as temporal and impulse-related variables, its ability to accurately capture rapid impact-related variables remains limited. Future studies should explore the use of higher sampling frequencies and improved estimation algorithms to enhance the accuracy of peak-force estimation during landing tasks.

Vertical jump and landing tasks are among the most commonly used functional movements in sports performance assessment and are widely applied in the evaluation of lower-limb explosive power, neuromuscular function monitoring, and injury-risk screening. Previous studies have demonstrated that the vertical GRF and impulse generated during the propulsive phase of a vertical jump are closely associated with jumping performance. Kirby et al. (Kirby et al., 2011) investigated the relationships among peak force, impulse during the propulsive phase, and jump height by manipulating countermovement depth during vertical jumps. Their findings indicated that impulse during the propulsive phase was positively associated with jump height, whereas peak force showed a relatively weaker relationship with jumping performance. Barker et al. (Barker et al., 2018) further reported that power output during the propulsive phase effectively reflects lower-limb explosive power and is significantly correlated with jumping ability. Therefore, accurate quantification of the kinetic characteristics during the propulsive phase is essential for performance evaluation. In addition to the take-off phase, the landing phase also represents an important component of human movement assessment. Niu et al. (Niu et al., 2014) reported that peak vertical GRF during landing is an important kinetic indicator for evaluating impact loading and injury risk. Similarly, Bates et al. (Bates et al., 2013) suggested that elevated peak vertical GRF during landing may increase the risk of anterior cruciate ligament injuries and other lower-extremity musculoskeletal injuries. These findings indicate that estimating vertical GRF characteristics during vertical jump and landing tasks using OpenCap may provide an objective and practical approach for evaluating movement performance and potential injury risk. Furthermore, compared with laboratory-based equipment such as force plates, OpenCap offers several practical advantages, including lower cost, greater accessibility, and easier deployment. These characteristics make it particularly suitable for large-scale and routine assessments in school physical education settings, where traditional biomechanical equipment is often unavailable. Consequently, OpenCap-based GRF estimation may provide a feasible solution for objective movement evaluation in educational, training, and community-based environments. Several limitations should be acknowledged. First, the sample

size was relatively small and consisted exclusively of undergraduate students majoring in physical education, which may limit the generalizability of the findings to other populations. Second, although both male and female participants were included, sex-specific analyses were not performed because the primary objective of this study was methodological validation. Future studies should include larger and more diverse samples and further investigate potential sex-related differences in OpenCap-based GRF estimation. In addition, future studies should incorporate waveform-based analyses, such as RMSE and statistical parametric mapping, to further evaluate the agreement between estimated and measured GRF signals throughout the entire movement cycle.

## 5. Conclusions

The method of estimating vertical GRF using segmental kinematic data obtained from the OpenCap markerless motion capture system, combined with center-of-mass acceleration and Newton's second law, can effectively estimate vertical GRF characteristics during vertical jump and landing tasks. This approach provides a novel means of obtaining GRF data during jumping and landing movements in everyday settings and offers a feasible solution for large-scale, routine assessments and movement-risk screening in school physical education environments.

However, certain impact-related variables, particularly peak force during the landing phase, still exhibited considerable estimation errors. Therefore, caution should be exercised when interpreting these variables in practical applications. Despite these limitations, OpenCap demonstrates substantial potential as a low-cost and accessible alternative for monitoring movement performance and assessing kinetic characteristics outside traditional laboratory settings.

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**Data Availability Statement:** The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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**Declaration of the Use of Generative AI and AI-Assisted Technologies in the Writing Process:** During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to improve the academic English language, grammar, style, and clarity of the manuscript. After using this tool, the authors carefully reviewed, revised, and verified all content. The authors take full responsibility for the accuracy, integrity, and scientific conclusions of the work.

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