CORRELATIONS BETWEEN HEELSTRIKE IMPULSIVE LOADING AND JOINT KINEMATICS OF THE LOWER EXTREMITIES DURING NORMAL LEVEL WALKING

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ABSTRACT

Impulsive loading by the ground reaction force (GRF) around heelstrike during walking is closely related to joint degeneration and might be affected by joint movement of the locomotor system. Fifteen healthy males (age: 25.5 ± 3 years) were studied to investigate the association between the quantitative joint angles, angular velocities and accelerations of the lower-limb joints, and the loading rates of the GRF. Apart from the gait speed, both the ipsilateral kinematics during the swing phase, and the contralateral kinematics around the beginning of the terminal double limb stance (DLS), may significantly contribute to the heelstrike and maximum loading rates of the GRF. The magnitude of the heelstrike impulsive GRF was particularly affected by the peak ankle dorsiflexion velocity during the swing phase of the ipsilateral limb. However, for generating the maximum loading rate of nearly eight times the magnitude of that of the heelstrike one needed more kinematic variables to be modulated in advance, especially the knee flexion velocities around the beginning of the terminal DLS of the contralateral limb. Knowledge of the joint mechanics of the locomotor system for controlling the magnitude of the impulsive GRF during normal walking might be helpful for gait retraining for the elderly or patients who might have excessive impulsive GRF and a high risk of joint degeneration.

Keywords: Heelstrike impulsive loading, Joint kinematics, Gait.

1. INTRODUCTION

Knee osteoarthritis (OA) is the most common form of degenerative joint disease, characterized by damaged articular cartilage [1], affecting at least 10% of adults over the age of 55 years [2]. Mechanical factors are considered a critical cause that initiates and progresses the degenerative OA [3-7]. Increased peak contact joint stress was found to hasten the development of OA [8]. A casual relation was also noted between the ex-

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cessive, repetitive impulsive loading experienced at heelstrike during level walking and the development of degeneration of articular cartilage in the lower extremity [5,7,9-16].

Heelstrike impulsive loading, or the heelstrike transient, is described as an impulse of the vertical component of the ground reaction force (vertical GRF) experienced at heelstrike during level walking. It appears at about 10% of the stance phase with a duration of 5-25ms, a magnitude range 0.5-1.25 times body weight, and a frequency range of 10-75Hz [17,18]. Increased loading rates of the impulsive GRF suggest a reduced ability for shock absorption [19,20] resulting in an excessive transient GRF propagating through the articular cartilage of the lower limb joint, thus degenerating the cartilage. Apart from accelerating fibrillation of the already damaged cartilage [21] – as observed in severe OA cartilage – increased loading rates at joints have also been linked to the initiation of OA in adjacent joints [22,23]. Therefore, understanding the aetiology of heelstrike impulsive loading may be helpful for preventing and treating joint degeneration.

Previous studies have suggested that active movements of the lower extremities contribute to the changes in the impact of the foot against the ground at heelstrike [7,14,24-26], and Collins even considered that alteration in joint movement of the human locomotor system is the most effective strategy for protecting the body from harmful impulsive GRF [7]. Different magnitudes of the heelstrike transient can be experienced in different individuals who use varied strategies of muscle control to decelerate the leg landing on the ground at the end of swing phase, even at the same walking speed [14,24,25]. Evidence that changes in the movement control may result in a more rapid rise of the GRF transient at heelstrike can still be found in subjects with paralysis of the quadriceps [9] and neuromuscular uncoordination due to tibiofemoral pain [25].

Verdini *et al*. [14] indicated that in the terminal swing phase, the activation of the biceps femoris and quadriceps muscles was used to control the knee joint for decelerating, stabilising and preparing the limb to land the ground, and that activation of the hamstrings was used to control the gradual knee extension that was caused by the quadriceps, thus reducing the heelstrike transient. However, the muscles of the quadriceps and hamstrings are biarticular muscles that have a multitude of actions [27]. Moreover, the musculoskeletal system in the human body has a redundant nature [28], *i.e.*, there are several joints and muscles which allow more than one musculoskeletal strategy for performing a certain multi-joint movement such as walking. Owing to such complex dynamics of the lower extremities, therefore, it is difficult to elucidate how individual muscles contribute to joint motion according to the activation patterns of the muscle's electromyogram alone [27,29]. Contraction of a muscle can control the acceleration of all joints, whether spanned or not [27], leading to changes in the joint velocity and angles. Therefore, measuring the joint kinematics may offer an insight into the roles of muscles during walking [30], including the roles in the control of the magnitudes of the impulsive GRF. However, studies relating to the associations between the detailed quantitative joint kinematics including the joint angle, angular velocity and acceleration, and the loading rates of the vertical GRF remain limited. To the best of our knowledge, there was only one study that reported the differences in the joint angles in individuals with different heelstrike loading [11].

The purpose of the current study was to investigate the causal associations between the joint angles, angular velocities and accelerations at the hip, knee and ankle joints in one lower limb during the swing phase, as well as in the other lower limb during the terminal double limb stance (DLS), and the subsequent loading rates of the vertical GRF in the ipsilateral limb in normal adults. It was hypothesized that the loading rates of the vertical GRF would be affected not only by the kinematics during the swing phase in the ipsilateral leg, but also by the kinematics during the terminal DLS in the contralateral leg.

2. MATERIALS AND METHODS

Fifteen healthy males who were free of neuromusculoskeletal pathology that might affect gait participated in this study with informed written consent (age: 25.5 ± 3 years; body mass (BM): 67.4 ± 8.1kg; height: 173.7 ± 6.5cm; BMI: 22.4 ± 1.7). Permission to conduct the study was provided by the Institutional Human Research Ethics Committee.

In a gait laboratory, each subject performed six gait trials at a self-selected pace on an 8-meter walkway. Twenty-eight infrared retroreflective markers at positions described by Wang *et al*. [31] were used to track the motion of the body segments, namely the pelvis (anterior and posterior superior iliac spines) and each thigh (greater trochanter, mid-thigh, medial and lateral epicondyles), shank (head of fibula, tibial tuberosity, medial and lateral malleolus) and foot (navicular tuberosity, 5^{th} metatarsal base, big toe and heel). Three-dimensional trajectories of the markers were measured using a 7-camera motion analysis system (Vicon 512, Oxford Metrics Group, U.K.) at a sampling rate of 120Hz, and the ground reaction forces (GRF) were gathered from two forceplates (AMTI, U.S.A.) at a sampling rate of 1080Hz.

For dynamic analysis the pelvis and the lower limbs were modeled as a 7-link system, each link embedded with an orthogonal coordinate system with the positive *x*-axis, *y*-axis and *z*-axis directed anteriorly, superiorly and to the right, respectively. The rotational movements of each joint were described with a cardanic rotation sequence (*z*-*x*-*y*) [32]. The sagittal-plane angular velocities and acceleration of the hip, knee and ankle joints were calculated by the generalized cross-validatory spline (GCVSPL) method [33] applied to the sagittal-plane joint angles during a gait cycle that was considered from the start of the swing phase, *i.e.*, the toe-off, to the end of the following stance phase. For subsequent statistical analysis, peak values of the sagit-

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tal-plane joint kinematics during the swing phase, as well as values of the sagittal-plane joint kinematics at the toe-off and at the end of the swing phase, were extracted. The stride length and stride time were calculated as the distance between and the period during two subsequent contacts of the same foot with the floor, respectively. Gait speed was calculated as the ratio of the stride length and the stride time. The step width was calculated as the distance between the two feet during DLS along the line perpendicular to the line of progression over the ground. The maximums of the upward and downward accelerations of the heel marker during the swing phase were also extracted. Heelstrike and maximum loading rates of the measured vertical GRF, respectively, were calculated as the initial and maximum slope of the vertical GRF curve during the initial DLS that was smoothed and differentiated using the GCVSPL method [33] (Fig. 1). All the force-related data were normalized to individual BM to reduce the influence of different anthropomorphic features between subjects. Values of each variable that were obtained by averaging the data across the six gait trails from all the subjects were ensemble-averaged for subsequent description of the gait pattern.

To quantify the influence of the sagittal-plane joint kinematics on the heelstrike loading rates of the vertical GRF, the correlations between the heelstrike loading rates and the joint kinematics during the swing phase in the ipsilateral limb, as well as the joint kinematics at the beginning of the terminal DLS in the contralateral limb, were analyzed by Pearson's correlation. To quantify the influence of the sagittal-plane joint kinematics on the maximum loading rates of the vertical GRF, the associations between the maximum loading rates and the joint kinematics during the swing phase in the same limb, as well as the joint kinematics during the terminal DLS and prior to the appearance of the maximum loading rate in the contralateral limb, were analyzed by Pearson's correlation. A correlation coefficient of 0-0.25 indicates no or low correlation, 0.26-0.50 a fair correlation, 0.51-0.75 a moderate to good correlation, 0.76-0.99 a good to excellent correlation, and 1.00 a perfect linear relationship. All significance levels were set at $\alpha = 0.05$. SPSS version 13.0 (SPSS Inc., Chicago, IL) was used for all statistical analyses.

3. RESULTS

The means of the heelstrike and maximum loading rates of the vertical GRF were 713.58 ± 117.48 and 5638.41 ± 2655.94%BM/s, respectively (Fig. 2). The average time to the maximum loading rates of the vertical GRF was 16.2 ± 11.95ms. The means of gait speed, cadence, stride length, stride time and step width were 1.12 ± 0.07m/s, 102.89 ± 7.52steps/min, 1.20 ± 0.05m, 1.08 ± 0.05s and 10.38 ± 1.96cm, respectively. The average maximums of the upward and downward accelerations of the heel marker during the swing phase were 15543.35 ± 3696.48 and 17405.1 ± 1954.29mm/s^2, respectively. The ensemble-averaged sagittal-plane

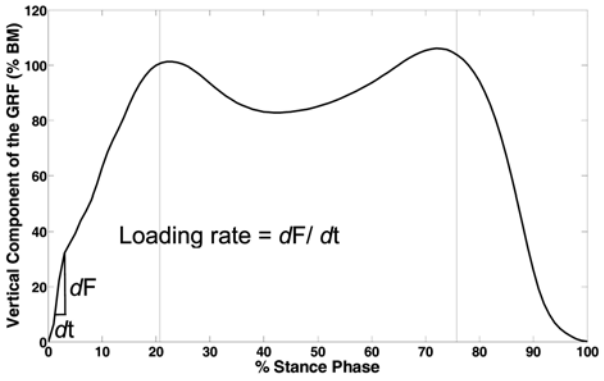


Fig. 1 A representation of the loading rate of the vertical component of the GRF. T1 and T2: The beginning and the end of the single limb stance, respectively

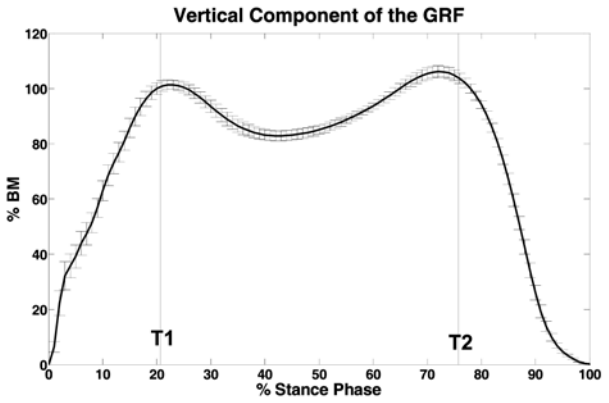


Fig. 2 The ensemble-averaged vertical GRF during normal level walking. Standard deviations are shown as gray error bars. T1 and T2: the beginning and the end of the single limb stance, respectively

joint angles, angular velocities and accelerations at the hip, knee and ankle joints during a gait cycle are shown in Fig. 3. The means of the ipsilateral joint kinematics during the swing phase and the contralateral joint kinematics during the terminal DLS are summarized in Tables 1-3.

Correlation analysis showed that both the heelstrike and maximum loading rates of the vertical GRF were significantly, positively correlated with the gait speed (correlation coefficients = 0.728 and 0.730, respectively; p = 0.002 and 0.002, respectively). The correlation between the two loading rates was good and significantly positive (correlation coefficient = 0.841, $p < 0.001$).

For the heelstrike loading rate of the vertical GRF, significant positive correlations were found in the peaks of the velocities of the hip flexion and ankle dorsiflexion, and the upward acceleration of the heel during the swing phase, while significant negative correlations were found in the peaks of the ankle plantarflexion and the downward acceleration of the heel during the swing phase (Table 1). The acceleration of the hip flexion and ankle dorsiflexion at the toe-off also significantly,

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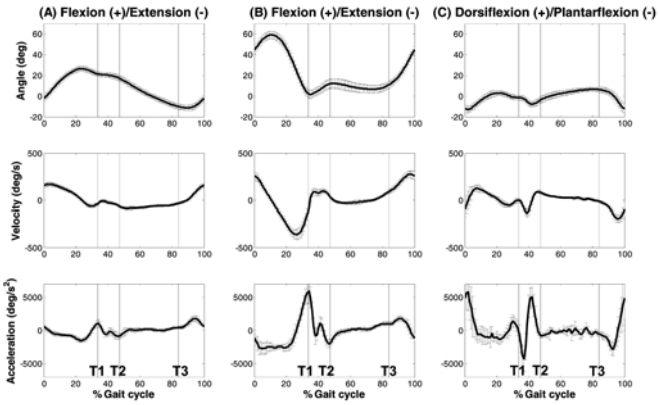


Fig. 3 Ensemble-averaged sagittal-plane joint angles, angular velocities and angular accelerations at the hip (column A), the knee (column B) and the ankle (column C) during normal level walking. Standard deviations are shown as gray error bars. T1, T2 and T3: the toe-off, the beginning and the end of the single limb stance, respectively

Table 1 Means (standard deviations) of the peak joint kinematics and peak acceleration of the heel during swing phase, and the Pearson's correlation coefficients between these kinematic variables and the loading rates of the vertical GRF

	Mean (standard deviation)	Pearson's correlation coefficient	
		Heelstrike loading rate of the vertical GRF	Maximum loading rate of the vertical GRF
Peak joint angle (degree)			
Hip flexion	26.65 (2.36)	0.425	0.405
Hip extension	0.33 (4.14)	–0.077	–0.031
Knee flexion	59.49 (3.80)	0.383	**0.580** *
Knee extension	–1.10 (4.10)	–0.215	–0.393
Ankle dorsiflexion	3.73 (2.87)	–0.133	–0.191
Ankle plantarflexion	14.02 (3.21)	**–0.631** *	**–0.611** *
Peak joint angular velocity (degree/s)			
Hip flexion	175.04 (21.06)	**0.531** *	**0.529** *
Hip extension	72.43 (19.38)	–0.334	**–0.522** *
Knee flexion	254.97 (55.27)	0.264	0.260
Knee extension	379.76 (55.45)	–0.413	**–0.780** **
Ankle dorsiflexion	176.23 (42.24)	**0.821** **	**0.572** *
Ankle plantarflexion	113.17 (18.94)	0.313	0.324
Peak joint angular acceleration (degree/s^2)			
Hip flexion	1481.25 (550.65)	0.166	0.360
Hip extension	1804.52 (213.82)	–0.478	**–0.595** *
Knee flexion	6767.59 (1943.10)	0.332	**0.629** *
Knee extension	4021.31 (737.63)	–0.503	–0.501
Ankle dorsiflexion	9415.72 (2374.47)	0.477	**0.640** **
Ankle plantarflexion	5209.33 (1869.49)	–0.387	–0.376
Peak acceleration of the heel (mm/s^2)			
Upward acceleration	15543.35 (3696.48)	**0.806** **	**0.852** **
Downward acceleration	17405.1 (1954.29)	**–0.711** **	**–0.619** *

positively correlated with the heelstrike loading rate (Table 2). In addition, a significant positive correlation was found between the heelstrike loading rate and the velocity of the knee flexion in the contralateral limb at the beginning of the terminal DLS (Table 3). Among the variables that correlated significantly with the heelstrike loading rate, the peak velocity of the ankle dorsiflexion and the upward acceleration of the heel during the swing phase showed the highest correlation coefficients of 0.821 and 0.806, respectively, indicating good to excellent correlations (Table 1).

For the maximum loading rate of the vertical GRF, significant positive correlations were found in the peaks of the knee flexion, the velocities of the hip flexion and ankle dorsiflexion, the accelerations of the knee flexion and ankle dorsiflexion, and the upward acceleration of the heel during the swing phase, while significant negative correlations were found in the peaks of the ankle plantarflexion, the velocities of the hip and knee extension, the acceleration of the hip extension and the downward acceleration of the heel during the swing phase (Table 1). The maximum loading rate also significantly, positively correlated with the ankle dorsiflexion acceleration at the toe-off, and negatively correlated with the ankle dorsiflexion acceleration prior to the heelstrike (Table 2). In addition, it also significantly, positively correlated with the contralateral-limb joint kinematics, including velocities of the hip and knee flexion, and the acceleration of the knee flexion at the beginning of the terminal DLS, as well as the peak velocities of the hip and knee extension during the terminal DLS (Table 3). Among the variables that correlated significantly with the maximum loading rate, the knee flexion velocity at the beginning of the terminal DLS and the peak of the knee extension velocity during the terminal DLS in the contralateral limb showed the highest correlation coefficients of 0.912 and 0.911, respectively, indicating excellent correlations (Table 3).

4. DISCUSSION

This study aimed to investigate the contribution of the sagittal-plane kinematics during the swing phase in the ipsilateral lower limb, as well as those during the terminal DLS in the contralateral lower limb to the heelstrike and maximum impulsive loading of the vertical GRF in healthy adults. Despite the maximum loading rate of the vertical GRF being about eight times the magnitude of the heelstrike loading rate, both loading rates were significantly associated with each other and with the gait speed. Our results also support the hypothesis that not only the joint kinematics during the swing phase in the ipsilateral lower limb, but also those during the terminal DLS in the contralateral limb, contribute to the heelstrike and maximum loading rates of the vertical GRF.

The average time to the maximum loading rate of the vertical GRF in the current study was comparable to that of 5-25ms reported in previous studies [17,18].

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Table 2 Means (standard deviations) of the joint kinematics at the toe-off and at the instance prior to the heelstrike, and the Pearson's correlation coefficients between these kinematic variables and the loading rates of the vertical GRF

Joint angle (degree) Angular velocity (degree/s) Angular acceleration (degree/s^2)	Mean (standard deviation)	Pearson's correlation coefficient	
		Heelstrike loading rate of the vertical GRF	Maximum loading rate of the vertical GRF
At the toe-off			
Hip flexion	–1.17 (3.04)	–0.239	–0.092
Knee flexion	46.24 (4.25)	0.135	0.417
Ankle dorsiflexion	–13.92 (3.52)	–0.396	–0.372
Velocity of hip flexion	160.25 (17.92)	0.224	0.391
Velocity of knee flexion	258.63 (42.91)	0.464	0.437
Velocity of ankle dorsiflexion	–70.48 (53.47)	–0.140	0.083
Acceleration of hip flexion	355.93 (309.18)	**0.591** *	0.382
Acceleration of knee flexion	–1780.07 (1050.09)	0.333	0.246
Acceleration of ankle dorsiflexion	6199.42 (2177.41)	**0.579** *	**0.677** **
At the instance prior to the heelstrike			
Hip flexion	21.10 (2.19)	0.073	–0.058
Knee flexion	1.48 (3.87)	–0.440	–0.422
Ankle dorsiflexion	–1.55 (2.40)	0.045	0.218
Velocity of hip flexion	–16.18 (15.06)	–0.216	–0.449
Velocity of knee flexion	26.51 (37.41)	0.258	0.244
Velocity of ankle dorsiflexion	–7.64 (21.24)	0.214	0.486
Acceleration of hip flexion	860.74 (490.96)	0.169	0.148
Acceleration of knee flexion	5101.68 (1650.17)	0.108	0.078
Acceleration of ankle dorsiflexion	–2218.14 (1369.42)	–0.257	**–0.564** *

Table 3 The Pearson's correlation coefficients between the loading rates of the vertical GRF and the contralateral joint kinematics during the terminal DLS, and the means (standard deviations) of the contralateral joint kinematics

Joint angle (degree) Angular velocity (degree/s) Angular acceleration (degree/s^2)	Mean (standard deviation)	Pearson's correlation coefficient	
		Heelstrike loading rate of the vertical GRF	Maximum loading rate of the vertical GRF
At the beginning of the terminal double limb stance (DLS)			
Hip flexion	–9.80 (2.63)	–0.115	0.048
Knee flexion	11.26 (4.41)	0.216	0.193
Ankle dorsiflexion	6.56 (2.29)	–0.126	–0.184
Velocity of hip flexion	–29.25 (13.55)	0.283	**0.555** *
Velocity of knee flexion	100.78 (31.84)	**0.610** **	**0.912** **
Velocity of ankle dorsiflexion	–11.44 (10.81)	–0.034	0.297
Acceleration of hip flexion	585.88 (216.45)	0.444	0.188
Acceleration of knee flexion	1138.53 (330.96)	0.491	**0.756** **
Acceleration of ankle dorsiflexion	–615.03 (585.05)	–0.317	–0.470
Peaks during terminal DLS and prior to the maximum loading rate of the vertical GRF			
Peak joint angle (degree)			
Hip extension	10.78 (2.75)	–	0.172
Knee extension	–12.42 (4.51)	–	0.248
Ankle dorsiflexion	6.45 (2.39)	–	–0.170
Peak joint angular velocity (degree/s)			
Hip extension	23.07 (13.39)	–	**0.596** *
Knee extension	–113.11 (34.40)	–	**0.911** **
Ankle dorsiflexion	–16.75 (11.62)	–	0
Peak joint angular acceleration (degree/s^2)			
Hip extension	–326.39 (223.69)	–	0.135
Knee flexion	2405.42 (323.13)	–	–0.095

However, the previous studies reported varied magnitudes of the maximum loading rate [11,23,25,34], and suggested that these arose from the differences in the gait speed, footwear, subject's age and the analysis method used [10,13]. The consequential influence of the gait speed on the loading rates of the GRF is supported by our result, namely that the heelstrike and maximum loading rates are significantly, positively correlated to the gait speed. Chen *et al*. also reported similar findings of the gait speed effect, namely that Caucasian females who walked fast displayed a greater heelstrike transient than Chinese females who walked slowly [10]. That is to say, walking slowly decreases the impulsive GRF in substance, and thus prevents the impact on the lower limb joint and may avoid degenerative joint diseases [10].

However, even at the same gait speed, changes in the heelstrike transient existed in different individuals using varied strategies to decelerate the leg before contacting with the ground [14,24,25]. In the current study, the maximum acceleration of the heel marker (the one that approximated the end of the lower limb) during swing phase also revealed good to excellent correlation with both the heelstrike and maximum loading rates of the vertical GRF (Table 1). Therefore, apart from the control in the gait speed, appropriate end-point control of the lower limb through proper adjustment in the joint movements for landing on the ground seemed to be one of the most critical determinants for the magnitudes of the impulsive GRF.

The magnitude of the heelstrike impulsive GRF was found to be significantly affected by the peak velocities of both ankle dorsiflexion and hip flexion, especially the former (correlation coefficient = 0.821: Good to excellent correlation, Table 1). Greater peaks of the

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flexion velocities of the ankle and hip joints that appeared at the initial swing phase may subsequently lead to a higher position of the heel during the swing phase. Such a higher position of the heel is beneficial for sufficient foot clearance [35,36], but it may result in a decreased upward acceleration of the heel at the subsequent heelstrike, implying a reduced braking ability of this swing limb. Thus, a greater heelstrike loading rate of the vertical GRF is generated. Increases in the accelerations of the hip flexion and ankle dorsiflexion around the toe-off may increase the peak velocities of the ankle dorsiflexion and hip flexion, and may therefore also contribute to the greater heelstrike loading rate (Table 2). In addition, based on their moderate to good correlation (Table 3), greater knee flexion velocity in the contralateral limb around its beginning of the terminal DLS may also subsequently increase the heelstrike loading rate of the GRF in the ipsilateral limb.

A good to excellent correlation between the heelstrike and maximum loading rates of the vertical GRF (correlation coefficient = 0.841) indicated that the heelstrike impulsive GRF might have a potential for predicting the maximum impulsive GRF, and vice versa. This could be supported by the results that most of the kinematic variables that were significantly associated with the heelstrike loading rate were markedly related to the maximum loading rate (Tables 1-3). However, the maximum loading rate showed a significant increase of nearly eight times the magnitude of the heelstrike's, suggesting that additional kinematic variables prior to the appearance of the maximum impulsive GRF needed controlling in order to generate such a large maximum loading rate. In the current study, changes in the knee flexion velocities around the beginning of the terminal DLS of the contralateral limb had the most critical influence on the magnitude of the subsequent maximum impulsive GRF (correlation coefficients > 0.9: Excellent correlations, Table 3). Increasing the knee flexion velocities around the beginning of the terminal DLS of the contralateral limb may contribute to more flexion of the contralateral knee, which is likely to result in greater downward movement of the body's center of mass and thus increased GRF. In addition, the correlation coefficient of −0.780 indicated that the reduction in the peak velocity of the knee extension during the swing phase of the ipsilateral limb may also significantly increase the magnitude of the maximum loading rate (Table 1). Variables such as knee flexion acceleration and hip extension velocity around the beginning of the terminal DLS of the contralateral limb, as well as peak velocity and acceleration of the hip extension during the swing phase of the ipsilateral limb, were all related to the changes in the magnitude of the subsequent maximum impulsive GRF, but with moderate to good correlations.

In conclusion, the current study was the first to report on which joint kinematic variables of the lower limbs in the sagittal plane contributed to the magnitudes of the heelstrike and maximum impulsive loading of the vertical GRF in the healthy adults. It was noted that the gait speed significantly affected both loading rates. In addition, the peak ankle dorsiflexion velocity during the swing phase of the ipsilateral limb was the most critical determinant for the heelstrike impulsive GRF, while the knee flexion velocities around the beginning of the terminal DLS of the contralateral limb were the most important factor in the maximum loading rate of the vertical GRF. This general picture of the joint mechanics of the locomotor system for controlling the impulsive GRF during normal level walking could be used as a reference for gait retraining with the aims of avoiding excessive impulsive GRF and thus preventing degenerative diseases in the elderly or in patients who have neuromusculoskeletal pathology of the lower limb such as anterior cruciate ligament-injured knees [37]. However, this study did not consider the frontal-plane joint kinematics that are frequently different from normal in patients with knee or hip OA who were found to display greater impulsive GRF. We also did not consider the possible differences in the joint kinematics and GRF transients between the loader and non-loader group [11]. In addition, a subject's age and neuromusculoskeletal condition of the locomotor system might contribute to changes in the impulsive GRF. Future studies may be dedicated to evaluating the influences of these factors on the magnitudes of the loading rates of the GRF for better a understanding of the pathomechanics of OA.

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