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Unloading Reaction during Sudden Ankle Inversion in Healthy Adults

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Abstract

The purpose of this research study was to determine the dynamics of early human response from sudden ankle inversion (30° tilt). Changes in vertical ground reaction forces (GRFs) following trapdoor release in a group of healthy subjects were compared to those from the similar experiments using a chair with two U shaped steel legs and matched weights of the human subjects. The experiments with the chair were further repeated with additional foam paddings at their bases to introduce visco-elastic properties to legs of the chair. Following the trapdoor release a decrease in the vertical ground reaction force under the inverting leg and subsequent increase in the supporting leg were observed in both human and chair experiments. The short onset of changes in vertical GRFs in our experiments indicate that the dynamic features of early response following trapdoor release are primarily due to mechanical events and may not be significantly affected by the neuromuscular reaction of human subjects.

Keywords

Ankle sprain; Sudden Ankle Inversion; Unloading reaction; Neuromuscular reaction; Mechanics

1. Introduction

Ankle sprain is the most common injury for sports participants, representing 15–20% of all sports injuries [1]. Among them 15%–60% may suffer from residual ankle symptoms: pain, swelling, “giving way” or feelings of instability, and recurrent sprains despite treatment [2].

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Conflict of interest statement

No financial or personal relationships exist between any of the authors with other people or organizations that could inappropriately influence this work.

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Sudden ankle inversion tests (SAI) from a standing position have been often used to understand neurophysiologic mechanisms behind ankle giving way. Several authors studied control of the ankle during SAI by examining muscle electromyography (EMG) [3–11]. Specifically, the onset of EMG signals recorded from peroneal longus muscle was considered an index of human response. Although EMG signals provide onset and amplitude of muscular activation, it is difficult to correlate EMG signals directly with muscle forces since the muscle length and velocity of change in length are not constant during a dynamic task. It is difficult to predict the body response during SAI based solely on EMG measurements.

In order to examine the dynamics of human reaction during SAI through an examination of changes in ground reaction forces (GRFs) under each foot, we developed a trapdoor device that provided sudden inversion on one ankle of a standing subject and record the GRFs underneath each foot. In a group of healthy subjects tested, we observed a significant weight shifting from the inverting foot to the supporting foot immediately after the trapdoor release. Our first impression was that such a weight shift might fit a model of a reduced vertical GRF on the inverting foot due to muscular reaction. However, the onset of such weight shifting took less than 20 milliseconds. No human neuromuscular system can generate force in such a short time frame unless the action is pre-planned. In our experiments, the pre-planned action was not possible as the trapdoor was released randomly to decrease anticipatory actions. Based on the short onset, we speculated that the body weight itself might be an important factor for the shift of weight during the early phase of SAI. We performed additional trapdoor experiments by substituting the human subject with a two-legged chair upon which a matching weight of a human subject was fixed. The purpose of these SAI experiments was to examine whether the short onset of weight shifting was primarily a mechanical event. To account for possible damping effect of soft tissue in the lower limbs of the subjects, the experiment was repeated with additional foam padding wrapped around the footing of the chair.

Here, we report the results of two sets of experiments, i.e. healthy adults and a chair with or without padding. Our purpose was to gain insight of the dynamics of early response of the human body during SAI. These experiments may help to understand whether or not human neuromuscular action can significantly influence a body's response.

2. Method

2.1. Human subjects

A total of 15 healthy adults (14 males, 1 female, age = 29.9 ± 6.2 years, height = 174.4 ± 7.4 cm, weight = 74.51 ± 12.55 kgs) volunteered for this study. Inclusion criteria were ages between 18 and 45 years and participation in recreational/competitive sports. The subjects were excluded if they had injury to lower extremities within last 12 months, history of severe lateral ankle sprain, joint disease or fracture in the lower extremities, vestibular deficits, insulin-dependent diabetes, or any systemic disease that might interfere with sensory input or muscle function in the lower extremities. Prior to testing, all subjects signed an informed consent approved by the Institutional Review Board.

2.2. Instrumentation

A customized trapdoor with a tilting platform was built for SAI testing (Figure 1a). The trapdoor was held in a level position by a deadbolt which, when released, allowed the tilt platform to rotate 30° before hitting a mechanical stop. A potentiometer was attached to the pivot joint of the tilt platform to measure the angular rotation. The tilting platform provided rubber straps to secure the subject's foot to avoid the lifting of the foot during the

experiment. The trapdoor and the stable platform were each positioned and secured over separate force plates, and were equal in weight and height.

The vertical GRFs from both feet were measured using two force plates (AMTI Measurements Group, Watertown, MA, USA). The signals from these force plates were sampled at a frequency of 100 Hz.

2.3. Experimental procedure

The subjects were familiarized with the equipment and testing procedures prior to testing. During testing, subjects stood with the left foot on a level stable platform and the right foot centered over the pivoting joint of the tilting platform. Subjects were instructed to stand still with eyes open, arms relaxed at their sides, and feet bare, parallel, and shoulder-width apart. The subjects wore a safety harness attached to the ceiling. To minimize anticipation the onset of trapdoor release was randomized and loud music on noise cancelling headphones was used. The subjects were instructed to maintain equal weight distribution on both feet. Subjects received five trials of SAI with 30° rotation on the tilting platform.

2.4. Additional chair experiments

A chair with two U shaped steel legs was used in additional experiments (Figure 1b). The purpose of these experiments was to determine whether an object with equal weight and two limbs might show similar early dynamic response as those of their human counterparts during SAI. Foam padding was wrapped around the footing of each chair leg for some experiments in order to increase visco-elastic properties of the system. It was, however, not intended to precisely mimic the characteristics of human soft tissue. Five different weights were utilized during the chair experiments to match the weight of five subjects randomly chosen (5 males, age = 33 ± 7.5 years, height = 173.8 ± 4.7 cm, weight = 65.63 ± 7.2 kgs). Chair tests, with matched weights, were repeated three times with padding (PAD) and without the padding (NPD).

2.5. Data processing and analysis

A Matlab (Mathworks Inc.) program was developed to process the recorded data. The program synchronized the data of the GRFs with angle of the tilting platform (Figure 2). The time intervals from the onset of trapdoor release to the onset of vertical GRF change (T_A and T_B) and peak GRF (T_C and T_D) were determined for the supporting limb and inverting limb, respectively. The onset of GRF change was defined as the beginning of a continuous change (either an increase or a decrease) in the vertical GRF.

The GRF response of the supporting and inverting limbs was quantified using the vertical force variation (VFV). The VFV from each foot was defined as the force difference between the baseline GRF and the vertical GRF at any time point of interest. Thus, the peak VFV (P_C or P_D) is the difference between the vertical GRF values at the onset of force change and at peak GRF for each foot.

3. Results

The 30° rotation of the trapdoor from the onset to the impact with the mechanical stop took 85.8 ± 17.2 ms for experiments in 15 subjects and 75.1 ± 6.7 ms for experiments in the weighted chair. The maximum velocity of the trapdoor rotation was $448.61^\circ/\text{s}$ in 15 subjects and $454.36^\circ/\text{s}$ in the weighted chair.

The onset of changes in vertical GRF with respect to trapdoor release occurred early on with mean T_B values for the human and chair experiments being -7.0 ± 4.6 ms and -37.6 ± 9.2 ms,

respectively (Table 1). Similarly, mean T_A value were 18.7 ± 7.2 ms and -27.4 ± 9.4 ms. The negative values of T_A and T_B were probably due to a fact that force sensors that detected the change in GRF were more sensitive than the potentiometer that detected release of the trapdoor. The former were able to pick up small change in force while the corresponding motion signal recorded from the potentiometer at the beginning of trapdoor rotation appeared less clear. In processing data of the onset of trapdoor release we skipped 2–3 noisy data points to keep the consistency that accounted for about 20–30 ms of time at a sampling frequency of 100Hz.

The inverting foot achieved peak vertical force earlier than the impact of trapdoor to the mechanical stop in 15 human subjects ($T_D = 69.3 \pm 14.8$ ms), chair with padding ($T_D = 58.0 \pm 64.3$ ms), and chair without padding ($T_D = 33.2 \pm 27.6$ ms) (Table 1). The supporting foot reached the peak vertical force much later than the impact of trapdoor, ranging from 107.5 ± 7.0 ms in chair without padding to 140.8 ± 11.7 ms in 15 subjects. A careful examination of figure 3 revealed that the increase in vertical GRF under the supported foot was quite small before the trapdoor impact (Figure 3). The impact of trapdoor led to a significant increase in the supporting limb's vertical GRF in human experiments as well as chair experiments.

The VFV in the inverting foot was negative (P_D), and the VFV in the supporting foot (P_C) was positive, indicating unloading of weight at one side and loading at the other side, respectively. The VFV magnitudes were normalized as the percentage of body weight. The magnitude of VFV was greater in the supporting foot ($P_C = 1.40 \pm 0.22\%$) than the inverting foot ($P_D = 0.98 \pm 0.09\%$) in 15 subjects (Table 1). Similar trends were observed in the 5 subjects ($P_C = 1.41 \pm 0.27\%$; $P_D = 0.93 \pm 0.08\%$), chair with padding ($P_C = 1.23 \pm 0.23\%$; $P_D = 1.14 \pm 0.10\%$), and chair without padding ($P_C = 2.06 \pm 0.18\%$; $P_D = 1.18 \pm 0.05\%$). The magnitude of VFV was greatest in the supporting leg for chair without padding.

4. Discussion

Our data from the healthy subjects showed a quick decrease in vertical GRF under the inverting foot and subsequently increase under the supporting foot after trapdoor release (Figure 3). In a previous study, we reported a pattern of weight shifting from the stimulated foot to the non-stimulated foot when nociceptive electrical stimulation was applied to an ankle during double-limb standing [12]. Did the early change in vertical GRFs after trapdoor release in the current experiment represent a similar reflexive human reaction? The answer for this question is clearly a “No” because of a key observation. The onset (-7.0 ± 4.6 ms) of vertical GRF decrease under the inverting foot was too quick to be explained by any human spinal reflex. The transmission time for a spinal reflex ranges from 32 to 72 ms [13]. If not due to a reflexive human response, there must be a different explanation. Unlike our previous study where standing platforms were stationary, the current experiments involved a sudden trapdoor release. One possible explanation could be that the quick change in vertical GRF occurred primarily due to movement of the body mass after trapdoor release and subsequent collision with the mechanical stop. This explanation was supported by an observation that the onset of GRF decrease under the inverting side occurred within 30 ms in both human and chair experiments. Furthermore, our results indicated that the increase in the GRF under the supporting foot was primarily caused by the trapdoor impact.

Although the basic patterns of early changes in vertical GRFs were similar, there were some differences noticed between the human and chair experiments. (1) The onset of peak vertical force (T_D) under the inverting foot in human experiments was later than that in chair experiments regardless of the padding condition. This observation indicated that muscle force against ankle supination in the human subjects might reduce the load on the trapdoor

and therefore slow down its rotation after trapdoor release. (2) When comparing the peak of VFV under the supporting foot, Pc in chair experiments without padding was greater than that in human experiments, but smaller in experiments with padding. The Pc reflected primarily the impact between the trapdoor and mechanical stop. Our finding indicates that general mechanical weight shifting by itself can generate a similar amount of Pc as human subjects, depending on the damping of the system. The damping in the lower limb of human subjects can decrease if muscle stiffness increases which would result in increased peak impact force.

The main objective of our study was to find out whether human reaction under sudden ankle stretching may influence the dynamics of body response and therefore, reduce the risk of ankle injury. Previous studies suggested that peroneal muscle reflexive activation or pre-activation of the ankle evertor muscles might be feasible in avoiding an ankle sprain [10, 14]. The role of muscle reflexive activation has been seriously challenged by experiments showing that ankle evertor muscles were less likely to be activated quick enough to prevent ankle sprain injury under a SAI [9, 15, 16]. Our results supported the notion that muscle reflex was unable to effectively influence the weight shifting to supporting foot under a SAI, even though the activation of peroneal muscle may slightly reduce the velocity of ankle supination. However, peroneal muscle pre-activation may help to prevent risky positioning of the ankle during landing. Therefore, it is advised to be cautious regarding the interpretation of our results.

Our experimental device and set up allowed us to examine the changes in GRFs under each limb. Many of the previous studies have measured muscle EMG in an attempt to understand the control strategy of SAI in both healthy and FAI subjects [3, 5–11, 15–18]. EMG is useful in determining the onset of activity of individual muscle after SAI, but unable to explain functional role of the activated muscle. For instance, early activation of the peroneous longus was once speculated to prevent ankle inversion during SAI [19]. In our study, however, there was no clear indication of stopped ankle inversion during testing. Rather, it was clearly indicated that the early unloading/loading reaction after trapdoor release was primarily due to a series of mechanical events.

The trapdoor tilting angle and angular speed used in our study were comparable to those used in past studies. We chose the trapdoor-tilting angle of 30° based on safety concerns for the subjects. This angle is within the range of angles (20° – 50°) reported in past studies [5, 7, 10, 17, 20]. The time duration of trapdoor rotation in our study was comparable with those reported by Konradsen et al. [10] (80ms) and Isakov et al. [21] (60–80ms), but shorter than the 110ms reported by Vaes et al. [3]. The difference in the time duration between this study and that by Vaes et al. can be attributed to either the difference in the total angles of trapdoor rotation or the position of foot placement with respect to the axis of rotation of the trapdoor. The maximum rotational speed of 448°/s is less than 559°/s reported by Kristianslund et al. (2011) [22] and 632°/s reported by Fong et al. (2009) [23] during the side step cutting task. Past studies have demonstrated that the maximal angular velocity of the ankle inversion varies with the tasks, for example, 595°/s during jumping on the tilting surface [11], 403°/s during walking tasks [24], 377°/s during 30° trapdoor tilt [25], and 383–668°/s during 50° trapdoor drop [26]. Our results were close to that reported in past studies during walking or trapdoor tilting. The differences in the maximal inversion speed may be explained by the different impact forces on the involved foot during various tasks [27].

One limitation of this study was the accuracy of the test in simulating a real ankle sprain. In actuality, ankle sprains commonly occur when body weight is distributed disproportionately onto the spraining ankle, and when the individual is in motion, rather than standing in the testing position. In our experiments, we intended to study ankle sprain injury as well as

ankle giving way. Many episodes of ankle giving way occur during walking; either stepping on an uneven surface or making a turn. We tested our subjects in bipodal rather than unipodal stance because it is close to the situation under which some ankle giving way episodes occur. Furthermore, unipodal stance is associated with large variations in postural control and angular velocity of the ankle [28, 29]. It would be very difficult to maintain the consistency in our experiments in terms of onset time and angular velocity, if we were to use unipodal stance. Tests using trapdoor protocol may, to some extent, approximate the ankle giving way scenarios when they occur during stepping on a stone or landing on another's foot. However, a trapdoor experiment may not be a good representative model for other types of ankle giving ways that occur during cutting maneuver or landing with a supinated foot. Another limitation of the current study was that chair had rigid legs and a narrow contact surface with the floor, while human subjects had multiple joints in lower extremity and much wider contact area with the platform surfaces. Those may contribute to the difference in response recorded during our experiments. Nevertheless, the chair experiments allowed us to examine the dynamic response from two major mechanical events: release of one leg on a trapdoor and the subsequent consequence collision.

The results from the current study indicated that humans may not be able to significantly alter features of unloading response following ankle inversion in trapdoor experiments. In our previous study, we investigated the modulation of unloading reaction and found greater response when the ankle was in a supinated position compared to neutral position [12]. However, in that study, the subjects were tested while standing on the supinated surface and there was no trapdoor involved. Therefore the unloading in our previous work was basically due to human reaction. The magnitude of unloading reaction in our previous study was much smaller compared to the unloading due to mechanical events recorded in the current study. In other words, the unloading due to mechanical events primarily dominated the response recorded in the current study. Future studies may include testing healthy subjects with nociceptive stimulation, 3D motion tracking system, and EMG in order to understand more about the motor control and functional behavior of the unloading reaction. Future studies should also include subjects with FAI for comparison with healthy subjects.

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Highlights

- The dynamics of early response following sudden ankle inversion (SAI) was studied.
- Vertical GRFs in healthy subjects were compared to weight matched chairs.
- Chair experiments were further repeated with padding and no padding beneath them.
- Quick decrease in GRF under the inverting leg was observed in all our experiments.
- The early response during SAI may not be affected by neuromuscular reaction.

Fig.1a

Fig.1b

Fig 1. Illustration of the experimental setup. The two force plates were positioned at the floor level. The tilt platform was held in a level position by a deadbolt which, when released, allowed the platform to rotate 30° to simulate SAI before hitting a mechanical stop.

Fig 2.

The time-force curves recorded from a subject indicates changes in vertical force during SAI on the supporting leg (solid line) and inverting leg (dotted line). Two vertical lines mark the onset (dashed line 1) and the end (dashed line 2) of tilt platform rotation. Four arrows point to the onset of vertical force change in supporting leg (A), onset of vertical force change in inverting leg (B), peak vertical force in supporting leg (C), and peak vertical force in inverting leg (D).

Fig 3.

The vertical force curves of the inverting and supporting legs recorded from a subject and corresponding two chair tests. The peak value of the chair test was greater (no padding) or smaller (with padding) than the subject's data. Fz1 represents the VFV in the supporting leg while Fz2 represents the VFV in the inverting leg.

Table 1

Processed group data (mean $\pm$ S.D.) from the SAI experiment.

Variable	Definition	15 subjects Mean $\pm$ S.D.	5 subjects (matched in chair experiments) Mean $\pm$ S.D.	5 weights of chair (with padding) Mean $\pm$ S.D.	5 weights of chair (No padding) Mean $\pm$ S.D.
T _A	Time from onset of platform tilting to onset of vertical force increase (supporting foot)	18.7 $\pm$ 7.2 ms	18.8 $\pm$ 7.0 ms	-15.6 $\pm$ 10.5 ms	-27.4 $\pm$ 9.4 ms
T _B	Time from onset of platform tilting to onset of vertical force decrease (inverting foot)	-7.0 $\pm$ 4.6 ms	-7.6 $\pm$ 2.6 ms	-26.5 $\pm$ 8.2 ms	-37.6 $\pm$ 9.2 ms
T _C	Time from onset of platform tilting to peak vertical force (supporting foot)	140.8 $\pm$ 11.7 ms	138.4 $\pm$ 5.5 ms	118.6 $\pm$ 21.2 ms	107.5 $\pm$ 7.0 ms
T _D	Time from onset of platform tilting to peak vertical force (inverting foot)	69.3 $\pm$ 14.8 ms	67.6 $\pm$ 15.9 ms	58.0 $\pm$ 64.3 ms	33.2 $\pm$ 27.6 ms
P _C	Peak VFV (supporting foot)	1.40 $\pm$ 0.22%	1.41 $\pm$ 0.27%	1.23 $\pm$ 0.23%	2.06 $\pm$ 0.18%
P _D	Peak VFV (inverting foot)	0.98 $\pm$ 0.09%	0.93 $\pm$ 0.09%	1.14 $\pm$ 0.10%	1.18 $\pm$ 0.05%

ms – milliseconds