

The influence of landing mat composition on ankle injury risk during a gymnastic landing: a biomechanical quantification

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Purpose: About 70% injury of gymnasts happened during landing – an interaction between gymnast and landing mat. The most injured joint is the ankle. The current study examined the effect of mechanical properties of landing mat on ankle loading with aims to identify means of decreasing the risk of ankle injury. *Method:* Gymnastic skill – salto backward stretched with 3/2 twist was captured by two high-speed camcorders and digitized by using SIMI-Motion software. A subject-specific, 14-segment rigid-body model and a mechanical landing-mat model were built using BRG.LifeMODTM. The landings were simulated with varied landing-mat mechanical properties (i.e., stiffness, dampness and friction coefficients). *Result:* Real landing performance could be accurately reproduced by the model. The simulations revealed that the ankle angle was relatively sensitive to stiffness and dampness of the landing mat, the ankle loading rate increased 26% when the stiffness was increased by 30%, and the changing of dampness had notable effect on horizontal ground reaction force and foot velocity. Further, the peak joint-reaction force and joint torque were more sensitive to friction than to stiffness and dampness of landing mat. Finally, ankle muscles would dissipate about twice energy (189%) when the friction was increased by 30%. *Conclusion:* Loads to ankles during landing would increase as the stiffness and dampness of the landing mat increase. Yet, increasing friction would cause a substantial rise of the ankle internal loads. As such, the friction should be a key factor influencing the risk of injury. Unfortunately, this key factor has rarely attracted attention in practice.

Key words: computer simulation, impact load, mechanical properties of floor mats, stiffness, dampness, friction

1. Introduction

In artistic gymnastics, regardless of male or female events, every performance ends with a landing. Previous study has shown that the success rate (or “stick the landing”, i.e., to bring the total body momentum to zero with a single placement of the feet) is appealing low [11]. Therefore, gymnastics landing skills have been becoming a vital determinant for outcomes of

competitions and present a significant challenge to gymnastic athletes at all levels. Due to various techniques (body kinematics and kinetics) performed prior to landings; gymnasts encounter a wide range of landing/impact conditions. Nonetheless, based on the basic principles of mechanics, once a gymnast departs from the apparatus, his/her flight time, body angular momentum and linear momentum of the total body center of mass during flight are determined. To prepare for the landing, a gymnast can only adjust his/her

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segments' position, velocity, and acceleration during airborne phase. In order to achieve an impressive/perfect finish, gymnasts always attempt to "stick the landing". As such, they must absorb a high impact force up to 14 times of their body weight (BW) during such a landing [12]. The loading to the musculoskeletal system could be even higher. Unlike other sports, gymnasts have to absorb the extremely high mechanical stress without shoes. Therefore, landing mats are the only effective contact materials to alleviate the impact forces during landings.

Previous study has shown that gymnasts would complete over two hundred times landings per week in their professional training and competition [4]. Consequently, repetitive impact loading is common practice for gymnasts. Impact force and/or dissipate energy during gymnastic landings can either be taken by landing mats or leg bones and muscles. Since athletes could not compensate the performance quality for reducing loading (i.e., "stick the landing"), the mechanical structure/property of landing mats would be the only factor that could balance between athletes' landing control and alleviating impact loading. Simply to say, gymnastics is a sport where competitive success is built up through intense and repetitive practices, a circumstance which potentially lends gymnasts to overuse and repetitive strain injuries (RSIs) in lower extremities. One relevant aspect which could alternate the process of RSIs [24] is to optimize the interaction between gymnasts and the landing mat by altering the mechanical structure/characteristics of the landing mats.

A descriptive epidemiological study has revealed that floor exercise has the highest injury rate among all events [12]. The majority of injuries of floor exercise happen during landings [3] and in lower limbs [7], [12]. The most injured joint is the ankle with an injury rate of 32%–36% [1], [12]. The most common reasons for ankle injuries are evoked from landings from great heights plus twisting and rotating [16]. Except for the loss of talent athletes, the medical costs for ankle injury treatments are unneglectable, for example, up to 227,000 dollars were compensated every year in New Zealand [1]. Improving the functionality of landing mats would both protect talent athletes and benefit our social system.

Due to competitive nature and standardization of landing mats, it is difficult to satisfy both safety and athletic performance. It is well known that, as airborne height increases, athletes could use more joint flexion for impact absorption during landings; but codes of FIG (Fédération Internationale de Gymnastique) related to deductions for landing encourage the gymnast

to use less joint flexion, resulting in the increase of injury risk [15]. On the other hand, a plausible relationship between mechanical properties of landing mats and injury risk has been investigated through various research avenues: (1) direct experiments [13], (2) mathematical modeling [14], and (3) computer simulations [5], [15]. Additionally, studies have further unveiled that the interaction between mechanical properties of landing mats and gymnasts is a key factor in the dissipation of impact forces [3] and is closely related to injury risk [5], [14]. In order to obtain suitable mechanical parameters of landing mats, pure mechanical material tests with rigid impactor were executed [14]. Compared with testing results with rigid impactor, video analysis was examined as a valid method to calculate the mechanical parameters of landing mat [19]. Based on the results of these related studies, some basic parameters, such as the dimensions, density, tensile strength, and compressibility of the foam used in floor exercise landing mats, were standardized by FIG. Although the results of pure mechanical tests were highly accurate, rigid impactor could not replace human movement completely. As such, pure mechanical tests with rigid impactor may not be appropriate for evaluating the alleviation effect of human internal loads, or the interaction between human body and the landing mats [15].

As it is the mechanical work performed by gymnasts that obviously causes injuries, an evaluation of mechanical process appears to be a logical first step. Biomechanical modeling permits not only quantification of the interaction between the human body and landing mats, but also analysis of the load intensity at joints [21], [24]. It is an effective tool for understanding what happens inside the body using information gathered from outside the body. From motion capture, anatomical positions can be obtained that allow the modeling of the skeletal structure [20], [22]. In such modeling, inertial characteristics of the body are estimated using anthropometric "norms" found through statistical studies [23]. Combined with motion capture information, the biomechanical (skeletal) model is able to determine the internal loads. Additionally, muscles can be modeled onto the skeletal frame using anatomical knowledge regarding normal attachment points. Thus, muscle lengthening and shortening can be determined in connection with skeletal movement. From these, bone-to-bone contact force and muscle loading/joint moment can be quantified (model simulation). It is known that all "modeling" involves simplifications of reality – and therein lies the method's strength (a means to understand complex systems without becoming lost in de-

tail) and its weakness (loss of detail). Until now, only few studies employed the biomechanical modeling approach to explore some aspects of the interaction between gymnasts and landing mats. Mills et al. [15] developed a seven-segment biomechanical model and three-layers landing mats model to assess the ground reaction force (GRF) and bone bending moments. The assessments were done through model simulation with adjustment of stiffness and dampness of landing mats. Obviously, the study focused on the influence of stiffness and dampness of landing mats on the vertical impact force. The weakness of the study was that it did not consider the surface friction existing between gymnast feet and the mats. As part of a resultant force, friction could alternate the effect of the impact force. Our knowledge of the interaction between gymnasts and the landing mats will remain incomplete until the effect of friction during the landing is considered and integrated into our understanding of the gymnasts landing. New studies are needed to bridge the gap.

The purposes of the current study were: (1) to explore and analyze how mechanical properties of landing mats, such as coefficient of stiffness, dampness and friction, change the impact force (external loads) and internal loads of ankle; and (2) to assess the generic risk of ankle injury [14], [15] based on external and internal loads analyses. The inquiry would illuminate friction during landing, laying a foundation for manufacturers to re-evaluate the design of landing mats from a more holistic perspective. It is the researchers hope that new designed products could reduce the injury risk of gymnasts.

2. Materials and methods

A. Participant

One elite male gymnast (age: 17 years, body height: 1.71 m, body mass: 55 kg) volunteered to participate in the study. The subject was a member of Chinese national gymnastics team and was healthy without any muscular or tendonitis injuries in lower limbs. The study was approved by Ethics Committee of China Institute of Sport Science.

B. Anthropometrical measurements

Forty-eight individual morphologic parameters, such as segmental lengths, sitting height, etc., were measured (Table 1). The data were used for building the fourteen-segment biomechanical model and its simulations.

Table 1. Measurement of individual morphologic parameters

| Body segment | | Size [cm] |
|---------------|--------------------------|-----------|
| Head and neck | Seated Ht | 67.3 |
| | Head Length | 7.7 |
| | Head Breadth | 6.0 |
| | Head to Chin Ht | 8.8 |
| | Neck Circum | 13.8 |
| torso | Waist Ht | 40.4 |
| | Chest Breadth | 11.3 |
| | Waist Depth | 7.1 |
| | Waist Breadth | 10.2 |
| | Chest Depth | 8.2 |
| | Shoulder Ht | 54.6 |
| | Armpit Ht | 46.4 |
| Upper limbs | Shoulder to Elbow Length | 13.6 |
| | Forearm Hand Length | 18.7 |
| | Elbow Circum | 11.3 |
| | Forearm Circum | 10.0 |
| Lower limbs | Thigh Circum | 19.4 |
| | Upper Leg Circum | 13.5 |
| | Knee Circum | 13.7 |
| | Knee Ht Seated | 20.9 |
| | Hip Breadth Standing | 12.4 |
| | Foot Length | 10.2 |
| | Foot Breadth | 3.7 |
| | Ankle Ht | 5.1 |
| Ankle Circum | 8.0 | |

C. Motion capture

Two high-speed cameras (EX-F1, CASIO Pty. Japan; 300 Hz) were used to record the landing movement of the gymnast. A framework (PEAK, with twenty-eight markers) was used for the three-dimensional calibration (based on algorithm of direct linear transformation) of the performance spaced. The accuracy of the calibration was within 3 mm.

After being informed about the test procedure and the possible risks involved in the study, the subject reviewed and signed a consent form for participating in this study. The gymnast first took fifteen minutes for warm-up, including light jogging, stretching and several easy acrobatic elements. Then, he repeated five times a skill: back handspring followed by salto backward stretched with 3/2 twist. Each trial was separated by three-minutes of recovery and a three-minute rest period. All trials were scored by three experienced international judicators independently. The scoring followed strictly the code of FIG 2013 [3]. The best trial was chosen (based on the highest score) for biomechanical analysis in this study. The selected trial was digitized by using SIMI Motion 3D analysis software for obtaining kinematic data. The raw kinematic data was filtered with second-order

Butterworth low-pass filtering (cut-off frequency: 6 Hz) for modeling analysis.

D. Biomechanical modeling and simulations

Combined with human body database Gebod in BRG.LifeMODTM, the body inertial parameters, such as link quality, center of mass, turning radius, were calculated by using the regression equations and personalized anthropometric data (Table 1). A fourteen-segment rigid body model was developed which consisted of head and neck, trunk, upper arms, lower arms and hands, upper legs, lower legs, and feet. Based on the international standard of gymnastics equipment [2], a computer model of floor landing mat with the dimension of 12 m × 12 m × 0.2 m (length × width × height) was developed by applying MSC.ADAMS software. The base of mechanical properties of the landing mat was obtained by a simple optimization algorithm (equations (1) and (2)) [10], and the model was validated by the curve of the dynamic changes (equation (3)) [5]. After approving the model, simulations were performed by modifying the base value of stiffness and friction of landing mat by: 90%, 110%, 120% and 130% as well as dampness by 95%, 105%, 110% and 115% for loading examination.

$$\Delta\delta = \sqrt{\frac{(x_1 - y_1)^2 + (x_2 - y_2)^2 + \dots + (x_n - y_n)^2}{n}}, \quad (1)$$

$$S = \left[\Delta V_{\text{sag}} + \Delta V_{\text{tran}} + \frac{1}{m} \sum_{i=1}^m \Delta \text{Joint angles} \right], \quad (2)$$

where x_i is the kinematic data from real performance, y_i is kinematic data from computer simulation, and $\Delta\delta$ is RMS (root mean square) error between real performance and simulation; ΔV_{sag} is expressed as the velocity in the sagittal plane, $\Delta \text{Joint angles}$ is expressed as root mean square error (RMS) of joint angles of lower limbs, n is the number of data with each curve, and m is the number of kinematic curves; the best optimal parameters are determined when S is the minimum.

$$CMC = \sqrt{1 - \frac{\sum_{i=1}^m \sum_{j=1}^n (Y_{ij} - \bar{Y}_j)^2 / n(m-1)}{\sum_{i=1}^m \sum_{j=1}^n (Y_{ij} - \bar{Y})^2 / (nm-1)}}, \quad (3)$$

where m is the number of all curves, n is the number of data in each curve, Y_{ij} is expressed as the j -th data of the i -th curve, \bar{Y}_j is the average of the j -th data of all curves, and \bar{Y} is the overall average of data of all

curves. If the result of the third equation is from 0.75 to 1, there is high similarity between the curves [5], [8], [25].

E. Loading analysis

In this study, the right ankle joint was chosen for the loading analysis. The selected time interval began with the big toe touch on the landing mat, continued to the peak of the GRF and ended at the 1st minimum of the GRF. The peak of vertical ground reaction force (PvGRF), time to PvGRF, the peak of horizontal ground reaction force (PhGRF), time to PhGRF, impulse, peak of loading rate, and ankle angle, knee angle and hip angle in the sagittal plane (i.e., joint flexion/extension) were analyzed during the selected interval for characterizing the loads. Additionally, the peak of ankle joint reaction force (PJRF), the joint torque in the sagittal plane, tibia index of lower leg (T_I) (equation (4)) [9] and the contribution of total work about the ankle joint muscle were also analyzed to quantify the internal loads.

$$T_I = \left| \frac{M_R}{(M_C)_R} \right| + \left| \frac{F_Z}{(F_C)_Z} \right| \quad (4)$$

where F_Z was expressed as stress force and M_R was expressed as moment bone.

3. Results

For a prove of the model validity, the comparison between the measured knee and ankle kinematics and the simulated ones based on a standard landing mat of floor exercise is shown in Fig. 1. The correlation analyses indicated that the simulation results of ankles and knees flexion/extension were highly correlated to the reality with coefficients of 0.95 for the left hip, 0.94 for the right hip, 0.99 for the right ankle, and 0.98 for the left ankle, respectively. As for the timing characteristics, there was a 3 ms difference in the time to the peak of GRF. However, the total time of both simulated and measured motion was identical (88 ms). The GRF of left foot, right foot and both are shown in Fig. 2.

The results of simulations unveiled that the influence of stiffness and dampness of the landing mat on the ankle's flexion/extension were substantial (Fig. 3a, b), while the consequence of friction was minimal (Fig. 3c). In general, the effects of stiffness and dampness on the ankle control were opposite to each other, i.e., the ankle's flexion/extension was inversely proportional to the stiffness and proportional to the dampness.

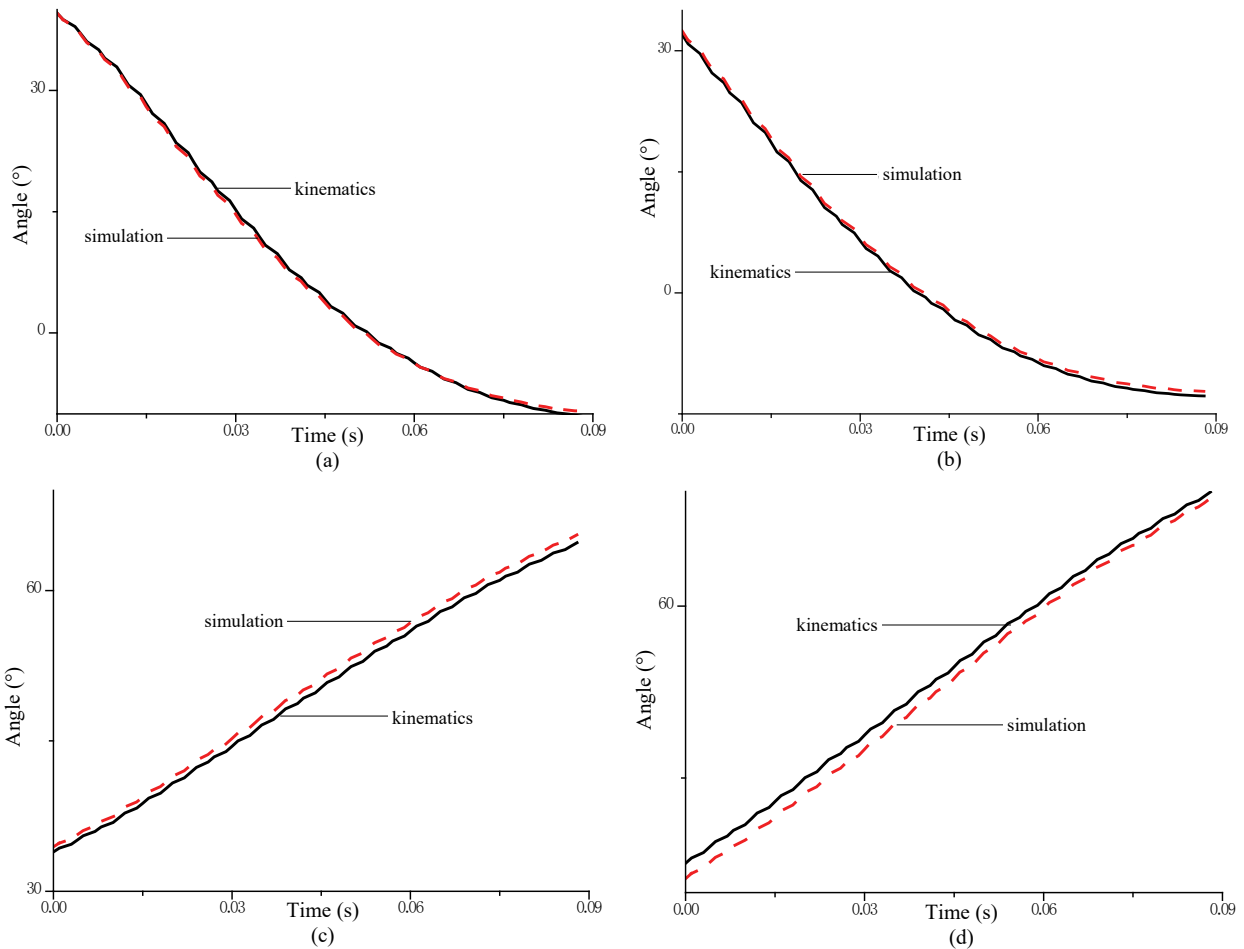


Fig. 1. Joint angles in the sagittal plane between simulation and real kinematic performance (a) right ankle, (b) left ankle, (c) right knee, and (d) left knee

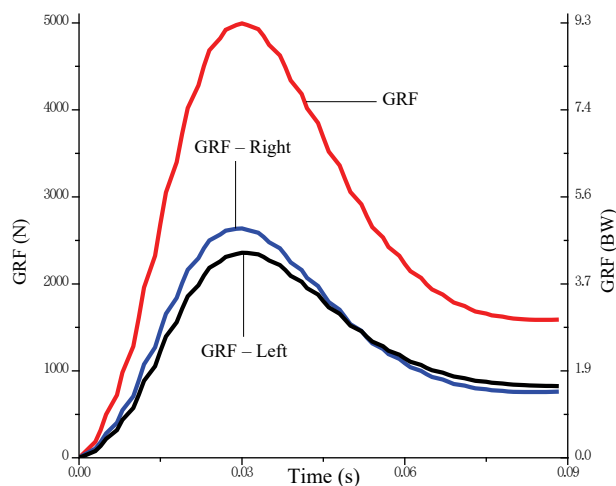


Fig. 2. GRF from simulation with standard properties of landing mat

The load analyses based on simulations of various mechanical properties of landing mat are shown in Table 2. Their dynamic changes over time are presented in Figs. 4 to 6. The results revealed the following trends. First, as the three property parameters (stiffness, dampness and friction coefficients) in-

creased, GRFv, GRFh, and JRF enlarged notably (Table 2, Fig. 6). Second, the harder the mat was, the faster the GRF (both vertical and horizontal component) and the JRF to their maximum (time in Table 2). Third, as stiffness and dampness coefficients increased, T_I increased as well. Fourth, the ankle joint

torque was remarkably amplified by the increase of the friction coefficient (Fig. 4). And last, a decrease in

the friction coefficient would reduce the foot horizontal velocity (Fig. 5).

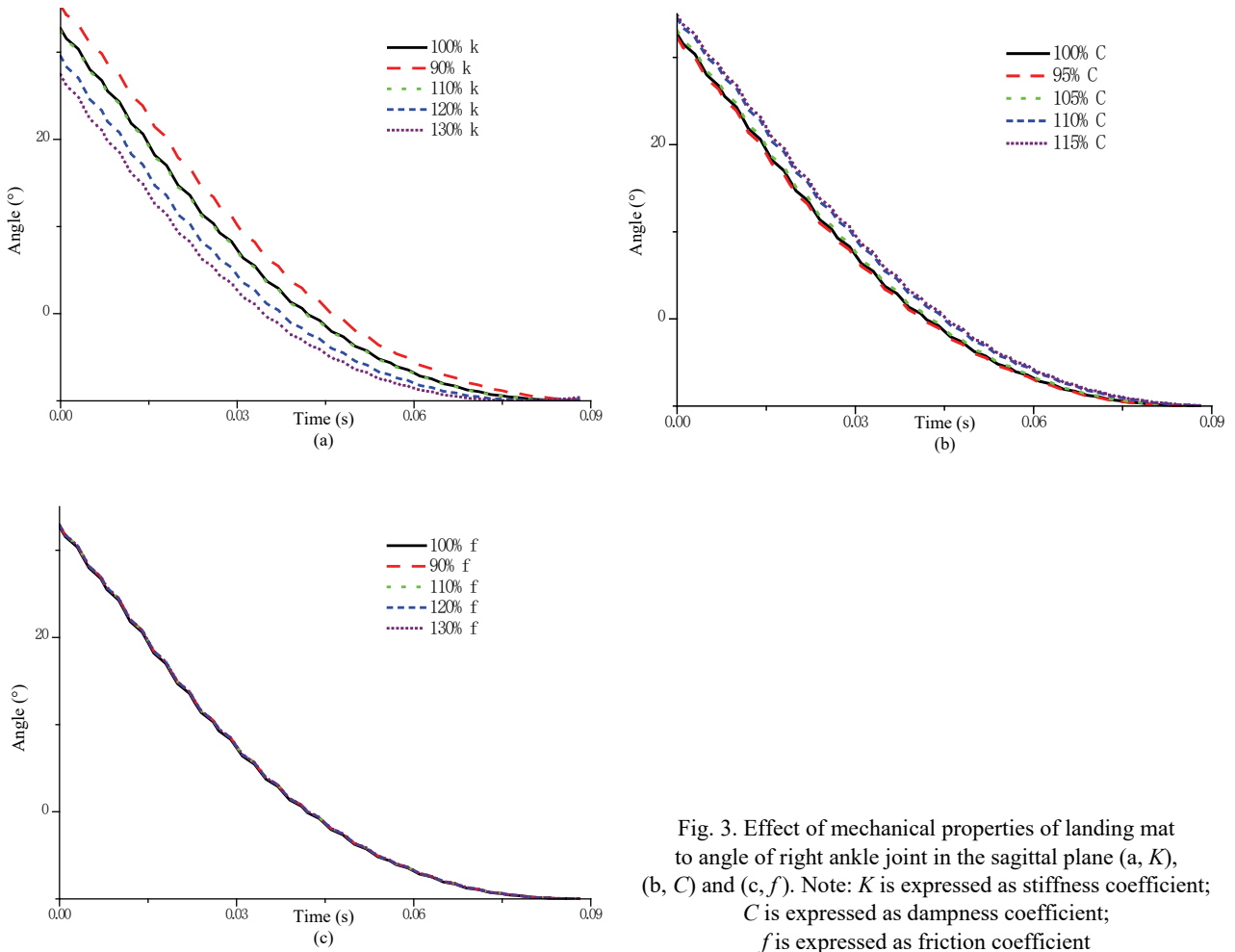


Fig. 3. Effect of mechanical properties of landing mat to angle of right ankle joint in the sagittal plane (a, K), (b, C) and (c, f). Note: K is expressed as stiffness coefficient; C is expressed as dampness coefficient; f is expressed as friction coefficient

Table 2. Effect of mechanical properties of landing mat to external and internal loads of right foot

| Mechanical properties | Standard 100% | K (%) | | | | C (%) | | | | f (%) | | | |
|-----------------------|---------------|---------|------|------|------|---------|------|------|------|---------|------|------|------|
| | | 90 | 110 | 120 | 130 | 95 | 105 | 110 | 115 | 90 | 110 | 120 | 130 |
| GRFv (BW) | 4.93 | 4.86 | 4.97 | 5.01 | 5.07 | 4.84 | 4.98 | 5.05 | 5.11 | 4.93 | 4.93 | 4.93 | 4.93 |
| Time (ms) | 38 | 42 | 36 | 34 | 31 | 38 | 38 | 39 | 39 | 38 | 38 | 38 | 38 |
| Loading rate (%) | 100 | 89 | 107 | 114 | 126 | 98 | 101 | 101 | 101 | 100 | 100 | 100 | 100 |
| GRFh | 3.16 | 3.11 | 3.18 | 3.19 | 3.2 | 3.15 | 3.2 | 3.23 | 3.27 | 2.99 | 3.29 | 3.47 | 3.57 |
| Time (ms) | 31 | 36 | 32 | 28 | 25 | 32 | 32 | 34 | 34 | 34 | 31 | 31 | 30 |
| JRF (BW) | 5.5 | 5.42 | 5.53 | 5.59 | 5.63 | 5.42 | 5.56 | 5.62 | 5.7 | 5.41 | 5.51 | 5.67 | 5.73 |
| Time (ms) | 38 | 42 | 38 | 34 | 31 | 38 | 38 | 39 | 39 | 38 | 38 | 38 | 38 |
| T_l (%) | 4.93 | 4.86 | 4.97 | 5.01 | 5.07 | 4.84 | 4.98 | 5.05 | 5.11 | 4.93 | 4.93 | 4.93 | 4.93 |

Note: GRFv is the peak of vertical GRF, GRFh is the peak of horizontal GRF, T_l is the lower tibia index of lower leg, and joint work is expressed as total work by muscles of ankle joint. Unit of loading rate, T_l and joint work was percent (%), which was compared with standard mechanical properties of landing mat. K is expressed as stiffness coefficient; C is expressed as dampness coefficient; f is expressed as friction coefficient.

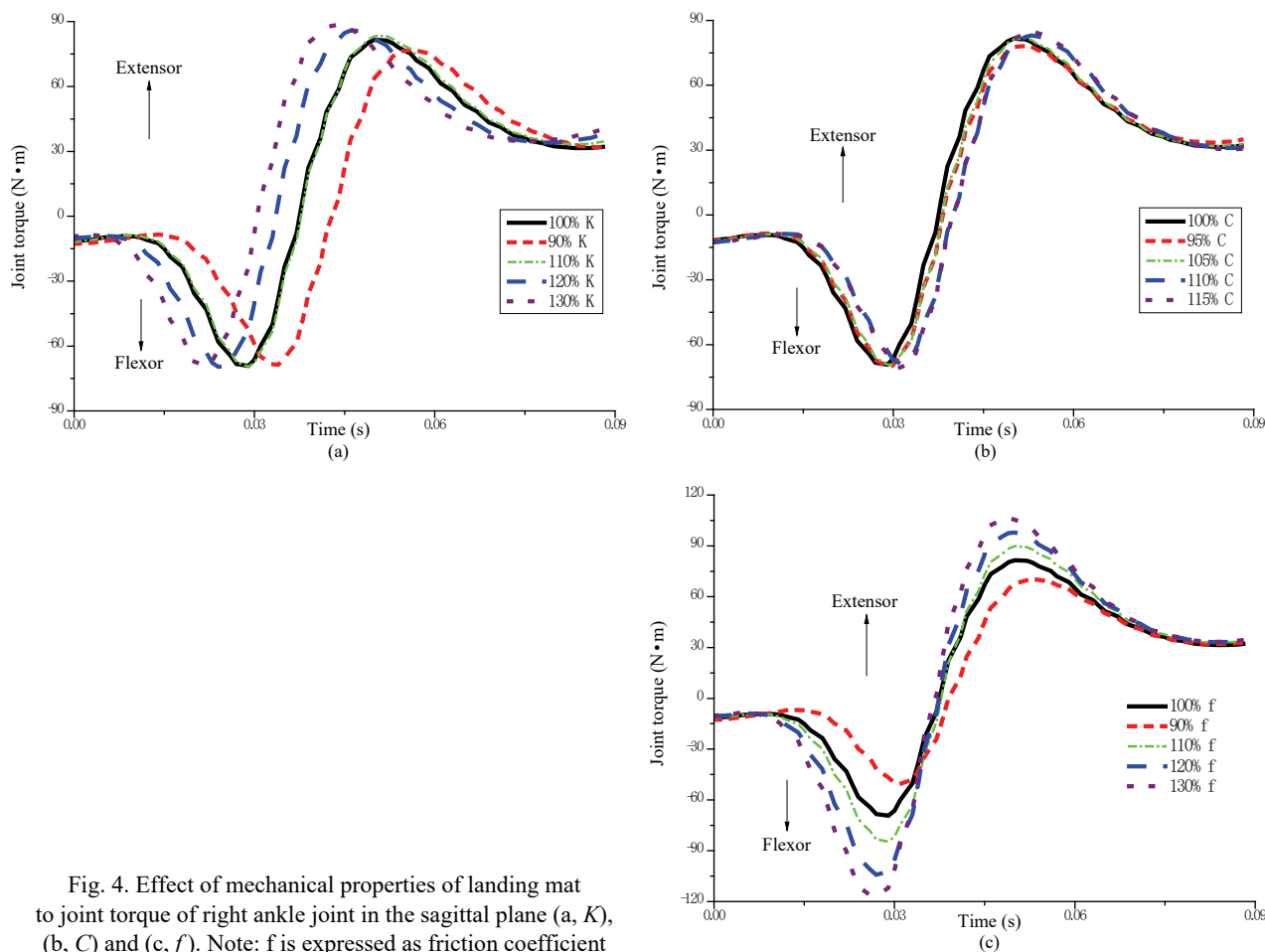


Fig. 4. Effect of mechanical properties of landing mat to joint torque of right ankle joint in the sagittal plane (a, K), (b, C) and (c, f). Note: f is expressed as friction coefficient

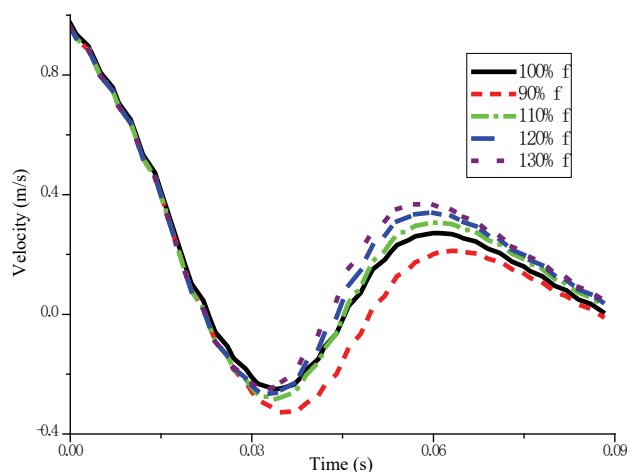


Fig. 5. Effect of friction of landing mat to horizontal velocity of right foot. Note: f is expressed as friction coefficient

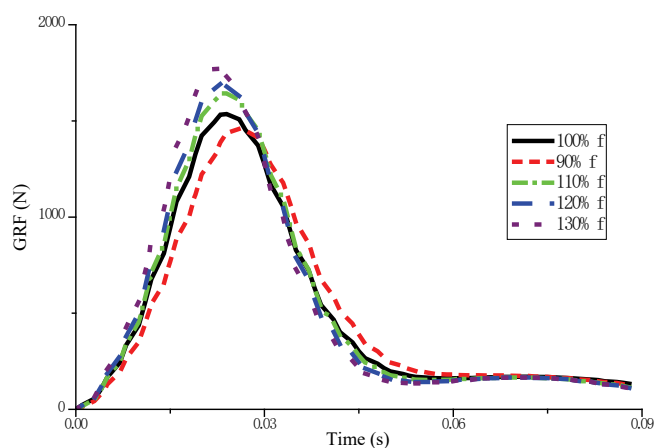


Fig. 6. Effect of friction of landing mat to GRFh of right foot. Note: GRFh is the peak of horizontal GRF; f is expressed as friction coefficient

4. Discussion

Computer simulation is a useful tool to assess the interaction between gymnasts and the landing mat in

order to evaluate the injury risk [14]. Previous study has revealed that the validity and reliability of modeling method can be judged by the consistency (the time error) between model simulation and real performance [5], [8], [25]. The time error of the current

study is 3 ms, which is towards the more accurate end of the reported results: 2–5 ms [8], [25]. Hence, the model would reproduce a reality-like performance during its simulations.

One aim of this study was, by means of computer simulations, to quantify the influence of mechanical properties of landing mats on the change of impact force and internal loads of ankle. The results of current study suggest that appropriate mechanical properties of landing mat would help to keep a balance between improvement of performance and decrease of injury risk of lower limbs. Although previous studies unveiled that stiffness and dampness of landing mat would affect the peak of vertical GRF, loading rate [14] and ankle dorsiflexion range of motion [17], [18], their influences on internal loads, such as JRF and joint torque are hardly revealed [15]. The results of this study have bridged the gap by divulging: the larger the stiffness of landing mat is, the shorter the times to the peak of GRF, to the peak of ankle JRF, and to the peak of ankle joint torque. As such, harder mat would cause an increase of loading rate, leading to a possible eversion in the ankle joint. On the other hand, the simulation results also suggest that, as the dampness of landing mat increases, the time to the peak of the ankle joint torque would be delayed. The consequences could be to create a possible inversion of ankle joint and to reduce ankle loads. Such loading conditions may result in mechanical instability of the ankle joint, likely leading to ankle sprains [5], [8], [25]. Additionally, the increasing of dampness of landing mat may let gymnasts feel uncomfortable that could lead to an increase of injury risk of the forefoot portion [5], [8], [25]. Therefore, keeping mechanical stability of the ankle joint with appropriate stiffness and dampness of landing is relevant for both practitioners and mat producers.

Another aim of the study was to explore how friction is to change the internal load of ankle. The mechanical functions of mat surface friction during a gymnastic landing is to eliminate the horizontal momentum generated during taking-off and to stop body anterior-posterior swing by decreasing horizontal acceleration. The functions suggest that friction is directly linked to internal loading of the ankle joint. It has been proven that both joint torque and work of ankle (loads to muscles surrounding the ankle joint) are highly correlated to the peak of horizontal GRF [6]. As such, analyzing and assessing horizontal GRF would supply an effective means to understand internal loads variation related to the change of friction. A previous study has shown that internal loads (such as JRF, joint torque, joint work) are the key factors

to assess the potential risk of ankle injury [15]. Our study indicates that, when friction of the landing mat is increased by 30%, the muscles of ankle joint would dissipate about twice as much energy (189%) compared to the landing mat with standard mechanical properties. The results reveal that an increase of landing mat friction would cause a significant increase of ankle internal loads, as such, resulting in higher risk of injury. The result would suggest that friction should play an important role in the risk quantification and the injury prevention. Unfortunately, the friction effect of landing mat has rarely attracted attention from sports researchers, engineers and mat producers.

Inevitably, there are limitations in this study. Stiffness, dampness and friction represent the compressive mechanical properties of the landing mat in this study. Thus, the result would not be suitable for improvement of material of landing mat directly due to complex multi-layer structure of the floor exercise landing mat. Further studies are needed to investigate more details for practical applications.

5. Conclusions

During gymnastics landings, kinematic variability of ankle joint is influenced by stiffness, dampness and friction of landing mat. The variation of stiffness and dampness would affect both the force peak and the time to peak of external loads of the ankle joint. Generally, loads would increase as stiffness and dampness increase. Although the friction change of the landing mat has no obvious effect on the ankle angle during landings, its increase would cause a substantial rise of ankle internal loads. Thus, the friction of landing mat should be a key factor influencing the risk of injury. Unfortunately, this key factor has rarely attracted attention in practice. The findings of current study could provide a foundation for future investigations, focusing on how to improve gymnastics mat functions in order to reduce the risk of injury.

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