The Injury Risk Prediction of Firefighters with Biomechanical Parameters during Single- and Double-Leg Jumps

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Abstract: The incidence of knee injuries during firefighter training is high, but there is a lack of research on predictive factors and risk assessment for such injuries. Biomechanical assessments can provide a better understanding of how the body’s load changes during exercise, which may alter the risk of injury. Ten firefighters were recruited for our study. Each participant completed the FMS test and the single- and double-leg jump tasks. Motion information was collected and musculoskeletal models of the participants were constructed using OpenSim 4.4 to obtain the joint angle and joint moment. The peak GRF and CoM-CoP angle were also calculated. The findings showed a significantly larger PKFM ($p = 0.0195$), VAFM ($p = 0.0039$), and peak AP GRF ($p = 0.0039$) during the single-leg jump. The opposite performance was observed for KFA ($p = 0.0098$) and MPA ($p = 0.0273$). A stepwise multiple linear regression analysis was used to explore the relationship between these parameters and both the FMS score and the times of injuries. The risk of injury is higher in the single-leg jump compared to the double-leg jump. The biomechanical parameters of these two jumps can be used to assess sports injuries and to provide methods and references for injury risk monitoring during firefighter occupational training.

Keywords: sports injury; jump tasks; musculoskeletal model; stability

1. Introduction

Compared to other professions, firefighters face many ergonomic risk factors and are exposed to various musculoskeletal diseases due to the unique nature of their job [1]. Previous studies have shown that firefighters suffer from high levels of work pressure and face many physical and mental challenges [2]. In addition, work-related musculoskeletal diseases are associated with work pressure, high workload and demand, low work control, and monotony [3,4]. Training-induced injuries are the most common and prominent issue among firefighters’ occupational injuries [5]. Due to the need for firefighters to perform a large number of climbing, weight-bearing, running, and jumping tasks during training and task execution, the common injuries of firefighters are mainly concentrated on leg muscle strain, and knee and ankle joint injuries, which hinder firefighters’ effective training. Therefore, studies that help decrease the injury risk are necessary.

Many studies on predicting and evaluating sports injury risks have identified the Functional Movement Screen (FMS) score as a key parameter and have concluded that there was a predictive relationship between the FMS comprehensive score and injury development. For example, in studies on male firefighter recruits [6], college students [7], youth rugby [8], and US Army soldiers [9], the predictive relationship between FMS comprehensive scores and injury development was reported. However, it has been noted that the FMS has some shortcomings, including strong subjectivity and unsuitability for
real-time monitoring [10]. Therefore, in addition to the FMS, more objective parameters are needed to predict and evaluate the risk of sports injuries accurately.

In previous research on lower limb sports injuries, demographic information is typically considered as an objective influencing factor. Specifically, kinematic parameters such as smoking habits [11], anthropometrics [12], body mass index (BMI) [13], aerobic/anaerobic ability [14], joint rotation angle [15], and center of mass (CoM)-center of pressure (CoP) inclination angle [16] are often overlooked when focusing on health behavior variables. Biomechanical assessments can provide a deeper understanding of how the body experiences changes in load during exercise, thereby revealing potential injury risk factors during exercise, which has been confirmed in studies of different populations and various types of exercise. For example, a series of studies have pointed out the following: biomechanical dynamics and kinematic factors were shown to have an impact on anterior cruciate ligament (ACL) load and risk of ACL injury [17]; several key biomechanical factors (vertical ground reaction force (vGRF), hip flexion moment, and peak knee eversion moment) differed significantly between individuals with and without ACL injury [18]; knee joint abduction impulse and other biomechanical factors were identified as predictive factors for lower limb injuries during running [19]; and knee joint moment was one of the main predictive factors for ACL injury [20]. Similarly, the ground reaction force (GRF) was also an important factor in lower limb dynamics, providing an approximate measurement of the load on the lower limb musculoskeletal system [21]. As one of the biomechanical factors that are intuitive and easy to measure, the GRF is believed to be associated with overuse injuries in the lower limbs [22]. Another study explored the association between vGRF and running-related injuries and found that vGRF may be a risk factor for injuries in young runners [23]. It can be seen that biomechanical parameters play an irreplaceable role in predicting the risk of sports injuries and have been proven effective in many fields of injury risk prediction and assessment but have not yet been applied to the safety monitoring of firefighter training.

This study was focused on risk factors for sports injuries and the insufficient attention to biomechanical parameters in the field of firefighter training safety monitoring. We collected motion information during the single- and double-leg jumping movements that firefighters were commonly exposed to in their daily training with a high injury risk. We then deeply analyzed the biomechanical characteristics of firefighter sports injuries and constructed objective evaluation models for firefighter sports injuries using biomechanical parameters. This study aimed to identify biomechanical parameters that reflected the level of injury risk in selected movement paradigms and provide methods and references for injury risk monitoring during occupational training. It is hypothesized that significant differences in kinematic and dynamic parameters exist between these two jumps, and some of the parameters can be used for injury risk assessment.

2. Materials and Methods
2.1. Participants

The sample size for this project was determined using GPower 3.1 software. Ten male firefighters (age 25 ± 3 years, height 175 ± 5 cm, weight 71 ± 8 kg, BMI 23.1 ± 1.5, and the training period 4.35 ± 2.32 years) from the Nankai District Fire Rescue Brigade in Tianjin participated in this study. All participants were screened to ensure that they had no contraindications or other symptoms such as heart disease. One year after participating in the experiment, these firefighters were required to complete a questionnaire to report any lower limb sports injuries they experienced after the experiment. The questionnaire included information on the number, location, and causes of the injuries. The study was approved by the Ethics Committee of the University (TJUE-2023-014) and all participants provided informed consent prior to participation.
2.2. Functional Movement Screen

The Functional Movement Screen (FMS) is comprised of seven sub-tests: Deep Squat, Hurdle Step, In-line Lunge, Shoulder Mobility, Active Straight Leg Raise, Trunk Stability Push-up, and Rotational Stability. Each sub-test is scored on a scale of 0 to 3 based on the quality of completion, with a maximum score of 21. If a participant experiences pain during any sub-test, a score of 0 is given.

The FMS standard test includes three exclusion tests for Shoulder Mobility, Trunk Stability Push-up, and Rotational Stability. If the subject experiences pain during any of the exclusion tests, regardless of the quality of the corresponding main test action, the item is scored as 0. The subjects will first practice using the FMS standard test kit and complete the three exclusion checks for Shoulder Mobility, Trunk Stability Push-up, and Rotational Stability during the exercise process. If there is no pain during the exclusion check, the corresponding sub-items will be tested normally in the future. However, if there is pain during the exclusion test, the corresponding sub-items score will be directly calculated as 0, and no further testing will be conducted.

After the practice, they rested for 3 min and we then conducted a formal test to score after physical recovery. The testing protocol consisted of unilateral tests for the Deep Squat and Trunk Stability Push-ups sub-tests, each conducted three times. The remaining sub-tests were tested bilaterally, with three tests conducted on each side, resulting in a total of six tests conducted on both sides. The best unilateral performance was taken as the unilateral final score, while the average unilateral score was taken as the bilateral final score.

Throughout the formal testing, the participants were video recorded.

To reduce the impact of personal subjectivity on the final scoring results, two individuals simultaneously rated one subject, and then their respective scores were averaged. If there were significant differences in ratings between the two individuals, a re-judgment could be made by watching video recordings of the testing process.

2.3. Jump Landing Tasks

The participants were asked to jump onto a force plate with a height of 39 cm and a center span of 75 cm twice (Figure 1); the first was with a double-leg landing (Figure 1a), and the second was with a right-leg landing (Figure 1b). Participants were required to maintain a balanced posture during landing to prevent further jumping or significant body swinging. Before data collection, participants were allowed to practice and rest between each attempt to prevent fatigue. Three attempts were recorded for each jump task. The average of three measurements was used for the subsequent analysis.

![Figure 1](image.png)

Figure 1. Two jump paradigms: (a) double-leg jump and (b) single-leg jump.

2.4. Data Collection

Optical motion capture systems (Vicon Motion Systems Ltd., Oxford, UK) were used to collect three-dimensional coordinate data during the motion process, while force plates were used to collect mechanical data. The data recorded by 14 Vicon infrared cameras
The 3DGaitModel2392 is a lower limb model comprising two legs and a concentrated trunk segment. It has 23 degrees of freedom and 92 tendon actuators, enabling the simulation and analysis of human motion primarily driven by lower limb muscles. This model is frequently used for kinematic and dynamic analysis. The study employed the musculoskeletal model 3DGaitModel2392 to position 15 markers at bone landmarks. These included the bilateral anterior superior iliac spine, bilateral acromion, bilateral ankle joint, bilateral knee joint, bilateral posterior heel joint, head, sternum, and sacrum. Furthermore, cluster markers were placed on both thighs, calves, and feet, resulting in a total of 39 markers.

The occurrence of marker drops during the experiment is indicative of an unsuccessful outcome. We repeated unsuccessful experiments.

2.5. Data Processing

The data were preprocessed using Nexus 2.8.1 Software (Vicon Nexus; Vicon Motion Systems Ltd., Oxford, UK). The musculoskeletal model in Opensim was established by preprocessed data, adapting to the characteristics of each participant’s posture. Joint angles and joint moments were calculated using inverse kinematics (IKs) and inverse dynamics (IDs) tools, combined with the three-dimensional motion data and GRF data, based on the established musculoskeletal model of the participants in Opensim. Normalize IKs and IDs data to 101 data points using cubic B-Spline, while standardizing IDs data by height (Ht) and body weight (BW).

The CoM of the subjects was determined as the geometric center of the triangle enclosed by three markers: left antagonist superior iliac spine, right antagonist superior iliac spine, and sacrum. The double-leg CoP of the subjects was calculated from the single-leg CoP provided by each force plate and the corresponding vGRF.

The kinematic variables of interest include the range of joint flexion angle, and the CoM-CoP angle (the angle between the line connecting the CoM and CoP and the vertical line passing through the CoP). The dynamic variables of interest include the joint flexion moment and the peak GRFs. We used the mean and standard deviation (SD) values of the biomechanical variables.

This study used a stepwise screening method for multiple linear regression. Perform stepwise multiple linear regression using the kinematic and dynamic variables of interest in the two jumps as independent variables, and the total scores of the FMS and the times of sports injuries suffered by firefighters within a year as the dependent variables.

The data processing procedures mentioned above were all obtained through custom MATLAB R2023a (The MathWorks Inc., Natick, MA, USA) programs.

2.6. Statistical Analysis

Statistical analyses were performed between the two jumps to evaluate the observed differences. The Shapiro–Wilk test for normality was used to assess the homogeneity of variance (homoscedasticity) of each characteristic parameter between the two jumps. For data that were not normal or homoscedastic, a non-parametric Wilcoxon signed-rank test was performed. An alpha level of <0.05 was considered statistically significant. All statistical procedures were performed using MATLAB (The MathWorks Inc., Natick, MA, USA).

3. Results

3.1. Injury Characteristics

The mean follow-up period was 1.0 ± 0.1 years.

During the follow-up investigation, four new lower limb sports injuries occurred in three firefighters, all of which were non-contact injuries. Furthermore, three firefighters
experienced one or more re-injuries to the same knee joint. The remaining five firefighters did not sustain any lower limb sports injuries.

3.2. FMS Scores

The FMS scores of different participants are shown in Table 1.

Table 1. FMS scores for different participants.

<table>
<thead>
<tr>
<th>Participants</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.0</td>
</tr>
<tr>
<td>2</td>
<td>17.0</td>
</tr>
<tr>
<td>3</td>
<td>18.0</td>
</tr>
<tr>
<td>4</td>
<td>18.5</td>
</tr>
<tr>
<td>5</td>
<td>17.5</td>
</tr>
<tr>
<td>6</td>
<td>11.0</td>
</tr>
<tr>
<td>7</td>
<td>18.5</td>
</tr>
<tr>
<td>8</td>
<td>13.0</td>
</tr>
<tr>
<td>9</td>
<td>15.5</td>
</tr>
<tr>
<td>10</td>
<td>15.0</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>16.1 ± 2.5</td>
</tr>
</tbody>
</table>

3.3. Kinematic and Dynamic Parameters

The kinematic (range of knee and ankle flexion angle, CoM-CoP angle (MPA)) and dynamic (knee and ankle flexion moments during the landing phase (KFM and AFM) parameters, and the anterior/posterior and medial/lateral GRF (AP GRF and ML GRF)) results are shown in Figure 2.

Compared to the double-leg jump, the single-leg jump showed a significant decrease in the range of knee flexion angle (KFA) \((p = 0.0098)\), while no significant differences were found in the range of ankle flexion angle between the two jumps (Figure 3a). Significant differences were observed in the peak knee flexion moment (PKFM) and the valley of ankle flexion moment (VAFM) during the landing phase between the two jumps (PKFM: \(p = 0.0195\); VAFM: \(p = 0.0039\)) (Figure 3b). The results showed that peak AP GRF for the single-leg jump was significantly larger than that for the double-leg jump \((p = 0.0039)\), while there was no significant difference in peak ML GRF for these two jumps (Figure 3c).

Additionally, the CoM-CoP angle during the landing phase of the single-leg jump was significantly smaller than that of the double-leg jump \((p = 0.0273)\) (Figure 3d).

3.4. Stepwise Multiple Linear Regression

Table 2 and Figure 4 show the results of the stepwise multiple linear regression for various parameters and FMS scores (model 1). Table 3 and Figure 5 show the results of the stepwise multiple linear regression for various parameters and injury times (model 2). The variables considered in model 1 were KFA, PKFM, VAFM, and MPA, while those considered in model 2 were KFA, PKFM, AP GRF, and MPA. The parameters for the double-leg jump were prefixed with DLJ, while those for the single-leg jump were prefixed with SLJ.
Figure 2. The kinematic and dynamic parameters during the two jumps: (a) knee ROM, (b) ankle ROM, (c) KFM, (d) AFM, (e) AP GRF, (f) ML GRF, (g) CoM-CoP angle.
Figure 3. The results of the statistical analysis: (a) knee and ankle ROM, (b) the PKFM and the VAFM, (c) peak AP and ML GRF, (d) CoM-CoP angle. *: $p < 0.05$, **: $p < 0.005$.

Table 2. Stepwise multiple linear regression results of various parameters and FMS scores (model 1).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coeff. (SE)</th>
<th>95% CI</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLJ-PKFM</td>
<td>$-241.5880 (41.8157)$</td>
<td>$-323.5487$--$-159.6272$</td>
<td>0.0103</td>
</tr>
<tr>
<td>DLJ-VAFM</td>
<td>$-146.1730 (20.9038)$</td>
<td>$-187.1436$--$-105.2022$</td>
<td>0.0060</td>
</tr>
<tr>
<td>DLJ-MPA</td>
<td>$-0.5595 (0.2149)$</td>
<td>$-0.9808$--$-0.1383$</td>
<td>0.0802</td>
</tr>
<tr>
<td>SLJ-KFA</td>
<td>0.2070 (0.0434)</td>
<td>0.1219--0.2921</td>
<td>0.0175</td>
</tr>
<tr>
<td>SLJ-PKFM</td>
<td>117.3770 (21.6048)</td>
<td>75.0324--159.7218</td>
<td>0.0122</td>
</tr>
<tr>
<td>SLJ-MPA</td>
<td>$-0.7269 (0.3005)$</td>
<td>$-1.3159$--$-0.1379$</td>
<td>0.0943</td>
</tr>
</tbody>
</table>

Figure 4. The fitting result of the stepwise multiple linear regression model 1.
4. Discussion

It is necessary to assess and predict sports injuries for firefighters to guarantee their routine training. Therefore, our study investigated the risk factors (especially biomechanical factors) for firefighters’ sports injuries during jumping on one or both legs. This study innovatively combined biomechanical parameters with subjective scale scores and the times of sports injuries suffered by firefighters to construct sports injury prediction models. This study conducted FMS scoring and the kinematic and biomechanical analysis of single and double-leg jumping movements on 10 male firefighters. We found significant differences in KFA, PKFM, VAFM, MPA, and AP GRF under two different jumps. These parameters are important factors that may potentially effectively predict the risk of jumping sports injuries, revealing the characteristic patterns of muscle and bone injuries caused by the two different jumps in firefighters, and can provide a reference for preventing injuries. The results of stepwise multiple linear regression provided predictive models for sports injuries.

4.1. Range of Joint Flexion Angle

Previous studies have shown that strain in the ACL decreases with increasing knee flexion angle [24,25]. The studies of Boden et al. [26] and Jeffery T. Podraza et al. [27] suggested that during the landing phase, when the knee joint approached full extension, it led to a lack of absorption of the GRF, which may be an important component of non-
contact ACL injuries. It is reasonable that the range of knee flexion angle is an important predictor of the risk of a knee injury.

Compared to the single-leg jump, the double-leg jump required a significantly larger range of knee flexion angle. This may be due to the fact that in the double-leg jump, both legs land at the same time, and a larger range of knee flexion angles can be used to absorb the landing impact and maintain balance. In the single-leg jump, only one leg hits the ground, and if a larger range of knee flexion is used to absorb the impact of the landing, more powerful calf muscles are needed to support the body, which will lead to an excessive movement of the center of mass, making it more difficult to maintain balance, and the movement can only be accomplished with a reduced range of knee flexion. Referring to the findings of K A. Owusu-Akyaw et al. [28] and S Sasaki et al. [29], a low flexion angle was the typical knee posture for ACL injuries. Grassi et al. [30] also found that the majority of non-contact injuries occurred in the low knee flexion position. Therefore, the double-leg jump with a significantly greater knee flexion angle would be safer due to the fact that the patellofemoral contact area was directly related to the flexion angle, and altering the knee flexion angle affected the incidence and location of impact injuries [31], which in turn reduced the strain of the ACL and decreased the risk of injury. The results of Julien Favre et al. [32] suggested that increasing the knee flexion angle during jump landings may be an effective intervention to improve knee biomechanical risk factors associated with ACL injuries, which was similarly supported by our findings.

In summary, when accomplishing movements similar to a single-leg jump, attention should be paid to increasing knee and ankle flexion as much as possible while maintaining balance to absorb the impact of landing and reduce the risk of lower limb musculoskeletal injuries.

4.2. Joint Flexion Moment

Compared to the double-leg jump, the PKFM and the VAFM were significantly larger in the single-leg jump. This may be because, in the single-leg jump, only the right leg landed on the ground, and thus the right knee withstood a greater impact force than landing on both legs, requiring greater muscle strength from the leg muscles or muscle groups to support it. At the same time, the right ankle should also play a role in supporting the body and maintaining stability. In the double-leg jump, both legs landed on the ground at the same time, and the impact force for each leg was evenly distributed, resulting in a relatively lower demand for the strength of individual leg muscles or muscle groups. This suggested, in part, that the single-leg jump posed a higher risk of lower limb musculoskeletal injury. Similarly, Camilla De Bleecker et al. [34] suggested that individuals with knee overuse injuries observed less ankle flexion when reaching the peak GRF during the landing phase, resulting in a larger VAFM.

In summary, the single-leg jump required stronger muscle groups or muscle strength during the landing phase. If the leg muscle strength is weak and cannot provide sufficient support, it may increase the risk of lower limb musculoskeletal injuries. Our conclusion was consistent with those of B- O. Lim et al. [35], indicating that compared to the double-leg landing and vertical jump task, the single-leg landing task had a statistically significant correlation with the risk factors of an ACL injury.

4.3. Peak GRF

There was evidence to suggest a statistically significant correlation between an increase in the GRF and the incidence of lower limb injuries [11]. Yanyu Zhang et al. [36] pointed out
that the AP GRF was the key to providing the driving and braking force, and the ML GRF was closely related to lateral stability. The braking force may be involved in the storage of missile performance [37] to alleviate joint stress and reduce the risk of injury. The peak AP GRF was significantly different between these two jumps, which may suggest that the double-leg jump faced a more challenging braking requirement during the landing phase to allow the body to regain equilibrium in the anterior–posterior direction as quickly as possible to avoid falls and injuries.

4.4. CoM-CoP Angle

Mario Mekhael et al. [38] pointed out that an increase in the CoM-CoP angle was associated with an increase in instability. The instantaneous CoM-CoP inclination angle provided information about the ability to control the CoM relative to the corresponding CoP [16], and it also reflected the extent to which the CoM moved away from the base of support [39].

The CoM-CoP angle during the landing phase of the double-leg jump was significantly greater than that of the single-leg jump ($p = 0.0273$). Since it is easier to recover a steady state in the anterior–posterior direction after a double-leg landing, participants can achieve greater knee flexion through greater centripetal bending of the upper body, thereby reducing the burden on the knee joints and reducing the risk of a knee injury. Additionally, the ability to restore body stability after landing on both legs was stronger compared to landing on one leg, allowing participants to exhibit larger unstable postures during the landing process, i.e., a larger CoM-CoP angle.

4.5. Limitations

The number of participants included in this study was limited, resulting in a small sample size, which may have limited the statistical efficacy of the findings.

5. Conclusions

This study focused on the risk factors of sports injuries for firefighters and also addressed the lack of attention to biomechanical parameters in the field of firefighter training and safety monitoring. The analysis of multiple parameters of firefighters in two types of jumps showed that there were significant differences between different jumps in the KFA, PKFM, VAFM, and AP GRF. Meanwhile, this study innovatively combined biomechanical parameters with subjective scale scores and the times of sports injuries suffered by firefighters within one year after completing the tests to construct objective evaluation models for firefighters’ sports injuries. The results indicated that the single-leg jump poses a higher risk of injury than the double-leg jump, as evidenced by the need for a larger KFA, higher PKFM, VAFM, and peak AP GRF. However, participants may sacrifice the CoM-CoP angle for a safer knee landing pattern. The biomechanical parameters under the two jumps can be used for sports injury risk assessment and provide a methodology and reference for injury risk monitoring in firefighter occupational training.

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