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Regression relationships of landing height with ground reaction forces, knee flexion angles, angular velocities and joint powers during double-leg landing

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ABSTRACT

Ground reaction forces (GRF), knee flexion angles, angular velocities and joint powers are unknown at large landing heights, which are infeasible for laboratory testing. However, this information is important for understanding lower extremity injury mechanisms. We sought to determine regression relationships of landing height with these parameters during landing so as to facilitate estimation of these parameters at large landing heights. Five healthy male subjects performed landing tasks from heights of 0.15–1.05 m onto a force-plate. Motion capture system was used to obtain knee flexion angles during landing via passive markers placed on the lower body. An iterative regression model, involving simple linear/exponential/natural logarithmic functions, was used to fit regression equations to experimental data. Peak GRF followed an exponential regression relationship ($R^2=0.90$–0.99, $p<0.001$; power = 0.987–0.998). Peak GRF slope and impulse also had an exponential relationship ($R^2=0.90$–0.96, $p<0.001$; power = 0.980–0.997 and $R^2=0.90$–0.99, $p<0.001$; power = 0.990–1.000 respectively) with landing height. Knee flexion angle at initial contact and at peak GRF had an inverse-exponential regression relationship ($R^2=0.81$–0.99, $p<0.001$–$p=0.006$; power = 0.834–0.978 and $R^2=0.84$–0.97, $p<0.001$–$p=0.004$; power = 0.873–0.999 respectively). There was also an inverse-exponential relationship between peak knee flexion angular velocity and landing height ($R^2=0.86$–0.96, $p<0.001$; power = 0.935–0.994). Peak knee joint power demonstrated a substantial linear relationship ($R^2=0.98$–1.00, $p<0.001$; power = 0.990–1.000). The parameters analyzed in this study are highly dependent on landing height. The exponential increase in peak GRF parameters and the relatively slower increase in knee flexion angles, angular velocities and joint power may synergistically lead to an exacerbated lower extremity injury risk at large landing heights.

1. Introduction

Landing is an essential athletic task which is commonly employed during intensive sports activities like basketball, gymnastics and volleyball [1–3]. This task is also performed in high-risk military activities like obstacle courses and parachute landing [4–5]. During landing, the double-leg landing strategy is preferred as it provides stability and minimizes injury risk in various activities that involve different magnitudes of ground reaction forces (GRF). However, lower extremity injuries, such as bone bruises and ligament tears, may result when excessive GRF is present [1,5–7].

With the aim of identifying the factors involved in the mechanisms of landing impact injuries, many previous studies have performed motion analysis work on double-leg landing from various landing heights, comparing between genders, between soft and stiff landing styles, and between gymnasts and recreational athletes [8–12]. For instance, a double-leg landing study by DeVita and Skelly [8] found that female volleyball and basketball players exhibited a peak GRF of 2–3 bodyweights (BW) during stiff and soft landing tasks from a 0.59-m height; their results suggested that soft landing (high knee flexion) reduced the impact stress on body tissues compared with stiff landing (low knee flexion). McNitt-Gray [9] further tested landing heights of 0.32 m, 0.72 m and 1.28 m for gymnasts and these subjects achieved peak GRF ranging from 3.9 to 11 BW. Similarly, Seegmiller and McCaw [10] illustrated that both gymnasts and recreational athletes exhibited an increase in the peak GRF (2.2–5.7 BW) with the tested landing heights (0.3 m, 0.6 m and 0.9 m); furthermore, the gymnasts exhibited greater peak GRF than the recreational athletes during landing. The large GRF experienced by athletes during landing from a great height may contribute to high injury risk [13]. Moreover, the knee joint is largely responsible for the body's ability to absorb shock during

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ground contact [8,14]. The occurrence of low knee flexion during landing may lead to a weaker knee joint power [8], which reflects diminished shock absorption capacity, and is likely associated with knee articular cartilage lesions [14–18]. Additionally, Zhang et al. [19] demonstrated that the knee joint power increased with landing height, which suggested that the knee joint is a major contributor to impact energy dissipation during landing.

Though the reported GRF, knee flexion angles and joint powers from these previous landing studies were largely varied perhaps due to the different landing styles adopted between subjects, the collective results have implied that these parameters are closely linked to the landing height at which the task is executed; the greater the landing height, the larger the GRF, knee flexion angles and joint powers. However, there is a limitation to the landing height at which the landing task can be safely performed in a controlled laboratory setting. Hence, the magnitudes of these parameters are unknown at large landing heights beyond this limitation and yet this information is important for understanding lower extremity injury mechanisms.

The objective of this study was to investigate how the landing height would relate to the GRF, knee flexion angles, angular velocities and joint powers present during landing, by testing a range of heights (0.15–1.05 m) that were commonly adopted in previous landing studies. We hypothesize that the peak GRF, together with its relevant GRF slope and impulse, during landing increases exponentially with landing height while the knee flexion angles at initial contact and at peak GRF increase in an inverse-exponential manner with landing height. We further hypothesize that the knee flexion angular velocity and joint power also possess an inverse-exponential relationship with landing height. Understanding of the regression relationships of landing height with GRF, knee flexion angles, angular velocities and joint powers may facilitate the estimation of these parameters during landing from large heights.

2. Methods

2.1. Study subjects

The study was carried out at the Motion Analysis Laboratory, Department of Orthopaedic Surgery, National University Hospital (Singapore). Five healthy male subjects were recruited, with a mean [standard deviation] age of 21.8 [0.5] years, height of 1.75 [0.05] m and weight of 66.5 [10.5] kg, from the local university. The inclusion criterion was regular participation in recreational sports which was taken as involvement in any type of sports for at least three sessions per week with each session lasting for at least 30 min. Exclusion criterion was a history of lower extremity injuries/diseases that could

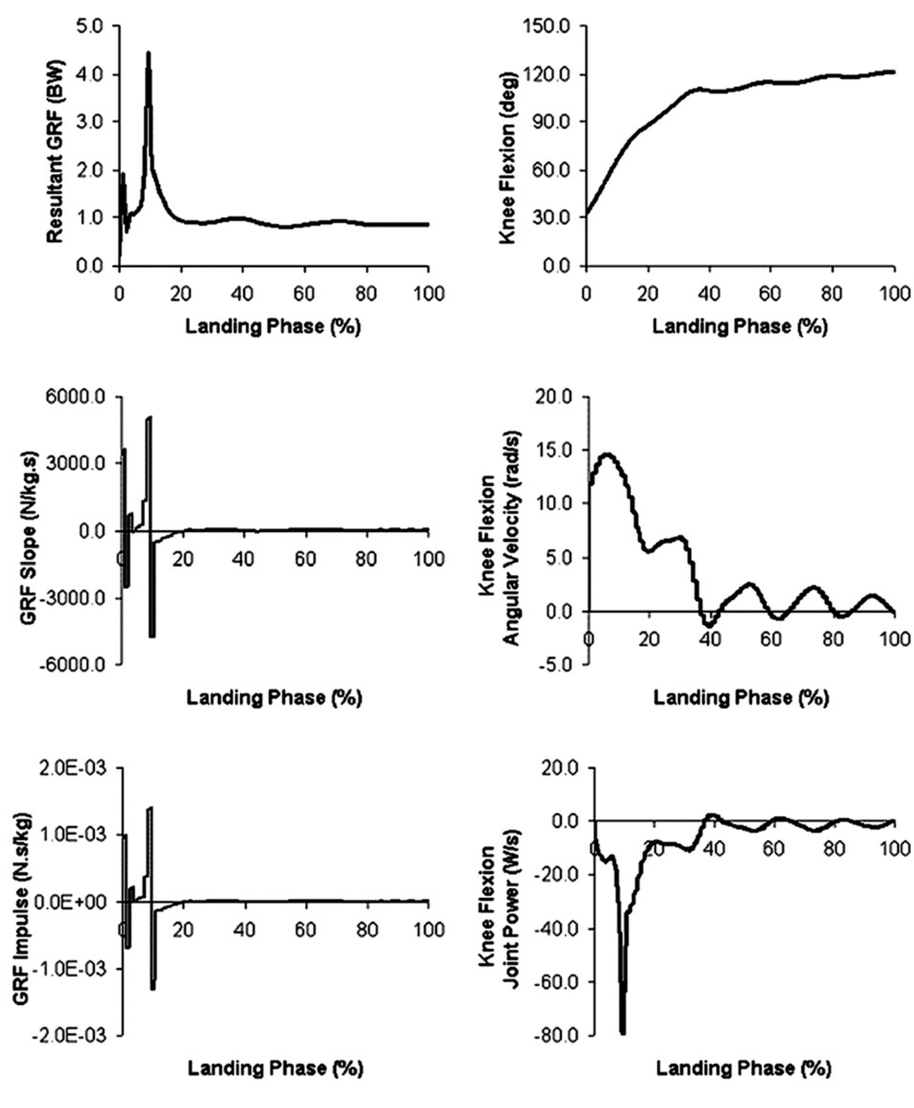

Fig. 1. Representative profiles of resultant ground reaction force (GRF), GRF slope, GRF impulse, knee flexion angle, knee flexion angular velocity and knee joint power during landing phase.

affect the landing biomechanics. Informed consent was obtained from the subjects, prior to the conduct of the study, in accordance with the university's Institutional Review Board. Anthropometric data, such as height, weight, knee width, ankle width, leg length and inter-anterior superior illiac spine distance, were acquired from all subjects.

2.2. Instrumentation setup

Two force-plates (Kistler, Winterthur, Switzerland), embedded into the floor, were employed to capture GRF data while a motion capture system (Vicon MX, Oxford Metrics, UK), comprising of six infra-red cameras, was utilized to collect kinematics data. The kinetics data were sampled at 1000 Hz and the kinematics data were sampled at 400 Hz. The software used for data collection and analysis were Vicon Workstation 5.1 and Polygon 3.1 respectively. The kinematics data were smoothed based on a Woltring filter with a mean squared error of 20. The force-plates were synchronized to the motion capture system. All systems were calibrated according to the manufacturers' recommendations prior to the commencement of the landing trials. Fifteen retroreflective markers (25-mm diameter) were attached to the lower body based on the Plug-in-Gait Marker Set, specifically on the sacrum and bilaterally on the anterior superior iliac spine, lateral thigh, lateral femoral epicondyle, lateral shank, calcaneus, lateral malleolus and second metatarsal.

2.3. Landing protocol

The double-leg landing task was performed by stepping off a height-adjustable platform with the dominant limb (preferred limb for kicking a ball) and landing bare-foot onto the force-plates. The subjects were not given special instructions regarding their landing mechanics so as to avoid experimenter bias, but were told to employ their natural landing style. The landing tasks were performed in the following sequence of landing heights: 0.15, 0.30, 0.45, 0.60, 0.75, 0.90 and 1.05 m. For each landing height, the subjects were given 3 min of practice and 5 min of rest before the actual landing trials were conducted for data acquisition. A successful trial is defined in which the subject steps off the platform (without an upward and/or forward jump action) and adopts a stable landing posture. For each subject, all trials were completed within 4 h. The resultant GRF, GRF slope (rate of change in GRF with time), GRF impulse (GRF integrated over time), knee flexion angle (at initial contact and at peak GRF), knee flexion angular velocity and knee joint power (product of knee flexion angular velocity and joint moment; joint moment was obtained using inverse dynamics) at the dominant limb were collected from the landing phase of five successful landing trials for each landing height per subject. The landing phase was defined as the time between initial contact and maximum knee flexion. GRF was normalized to body weight while the GRF slope, impulse and joint power were normalized to body mass.

2.4. Statistical analyses

The landing height (0.15–1.05 m) was taken to be the independent variable while the dependent variables were peak resultant GRF, GRF slope, GRF impulse, knee flexion angle (at initial contact and at peak GRF), knee flexion angular velocity and knee joint power. For each subject, all dependent variables were calculated for each trial and subsequently averaged across the five trials. Non-linear/linear regression (SigmaStat 3.1, SysTat Software Inc, USA) was used to find the curve/line of best fit that closely describes the value of the dependent variable, given the observed value of the independent variable. We applied non-linear/linear regression equations that involve simple linear, exponential or natural logarithmic functions to fit the experimental data. We used the Marquardt–Levenberg algorithm to find the coefficients of the independent variables that give the best fit between the equation and the data. It sought the values of the coefficients that minimize the sum of the squared differences between the values of the observed and predicted values of the dependent variable. We adopted an entirely iterative process, wherein the software began with a set of 'guessed' coefficients (input by the user), checked to see how the equation fits, then automatically continued to make better guesses until the differences between the residual sum of squares no longer decreased significantly (attained convergence). A R^2-value near 1 indicates a strong non-linear/linear regression relationship between the independent and dependent variables. A p-value less than 0.05 implies that the independent variable can be used to predict the dependent variables.

3. Results

Representative GRF data indicated the typical two-peak profile commonly observed during landing (Fig. 1). The peak GRF was achieved within 20% of the landing phase; similar observations were noted for peak GRF slope, GRF impulse, knee flexion angular velocity and knee joint power.

We found that the peak resultant GRF during landing typically followed an exponential regression relationship with landing height in the form of $y = ae^{bx}$, where y = GRF, x = landing height; the values for regression coefficients, a and b, ranged from 1.19 to 1.52 and 0.80 to 1.13 respectively (Table 1). Similarly for GRF slope, there was an exponential regression relationship with landing height, where a and b ranged from 267.8 to 1063.0 and 1.25 to 1.79 respectively. We also observed that the peak GRF impulse increased in an exponential manner with landing height, where a and b ranged from 5.0E−05 to 2.0E−04 and 2.01 to 3.51 respectively.

The knee flexion angles at initial contact and at peak GRF generally adopted an inverse-exponential (natural logarithmic) regression relationship with landing height in the form of $y = a\ln(x) + b$, where y = knee flexion angle, x = landing height. For the knee flexion angles at initial contact, the values for a and b ranged from 2.70 to 10.81 and 32.34 to 40.78 respectively. Regarding knee flexion angles at peak GRF, the values for a and b ranged from 2.97 to 12.52 and 64.10 to 67.38 respectively.

In terms of knee flexion angular velocity, the peak value increased in an inverse-exponential regression relationship with landing height, where a and b ranged from 2.40 to 6.27 and 12.38 to 16.59 respectively. For knee joint power, the peak value followed a strong linear regression relationship, $y = ax + b$, where y = joint power and x = landing height. The a and b values ranged from −54.04 to −27.59 and −2.36 to 2.01 respectively.

Between peak resultant GRF and landing height, we found a strong exponential regression relationship ($R^2 = 0.90$–0.99, $p < 0.001$; power = 0.987–0.998) for all the 5 subjects (Fig. 2). We also noted an exponential regression relationship ($R^2 = 0.90$–0.96, $p < 0.001$; power = 0.980–0.997) between peak GRF slope and landing height (Fig. 3A). Peak GRF impulse also had an exponential regression relationship ($R^2 = 0.90$–0.99, $p < 0.001$; power = 0.990–1.000) with landing height (Fig. 3B).

The knee flexion angle at initial contact had an inverse-exponential regression relationship ($R^2 = 0.81$–0.99, $p < 0.001$ to $p = 0.006$; power = 0.834–0.978) with landing height (Fig. 4A). Similarly, the knee flexion angle at peak GRF also possessed an inverse-exponential relationship ($R^2 = 0.84$–0.97, $p < 0.001$ to $p = 0.004$; power = 0.873–0.999) with landing height (Fig. 4B).

In addition, non-linear regression between peak knee flexion angular velocity and landing height revealed an inverse-exponential relationship ($R^2 = 0.86$–0.96, $p < 0.001$; power = 0.935–0.994) (Fig. 5A). Peak knee joint power demonstrated a substantial linear

Table 1
Typical non-linear/linear regression equations and corresponding regression coefficients obtained for Subject 1 with regards to the dependent variables: peak resultant GRF, peak GRF slope, peak GRF impulse, knee flexion angles (at initial contact and peak GRF), peak knee flexion angular velocities and peak knee joint power.

Dependent variables	Regression equations	Regression coefficients		R^2	p	Power
		a	b			
Peak resultant GRF	$y = ae^{bx}$	1.52	1.13	0.90	<0.001	0.987
Peak GRF slope	$y = ae^{bx}$	1063.0	1.64	0.95	<0.001	0.997
Peak GRF impulse	$y = ae^{bx}$	1.0E−04	3.51	0.95	<0.001	1.000
Knee flexion angle at initial contact	$y = a\ln(x) + b$	4.62	32.34	0.93	<0.001	0.978
Knee flexion angle at peak GRF	$y = a\ln(x) + b$	8.84	64.18	0.97	<0.001	0.999
Peak knee flexion angular velocity	$y = a\ln(x) + b$	2.40	12.51	0.96	<0.001	0.994
Peak knee joint power	$y = ax + b$	−54.04	−0.56	0.97	<0.001	1.000

A R^2-value near 1 indicates a strong non-linear/linear regression relationship between the independent (landing height) and dependent variables. A p-value less than 0.05 implies that the independent variable can be used to predict the dependent variables.

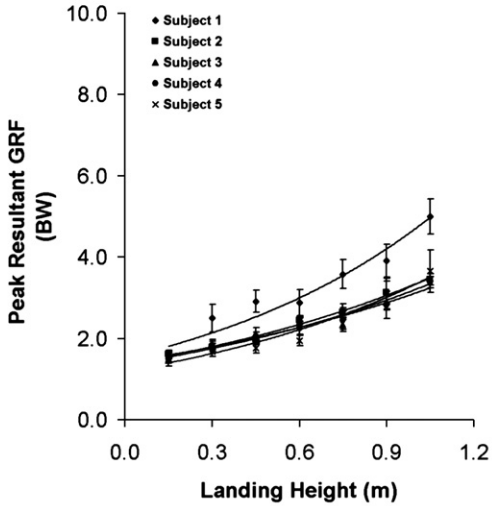

Fig. 2. Exponential regression relationships of landing height with peak resultant GRF for all subjects generally followed a $y = ae^{bx}$ equation, where y = peak resultant GRF, x = landing height, a,b = regression coefficients.

relationship ($R^2 = 0.98$–1.00, $p < 0.001$; power = 0.990–1.000) with landing height (Fig. 5B).

4. Discussion

In view of previous landing studies, the relationships of landing height with GRF, knee flexion angles, angular velocities and joint powers are not well understood and there is an existing limitation in obtaining these data at very large landing height in a controlled laboratory setting. Our study aimed to investigate these relationships through a series of landing tasks from a range of landing heights (0.15–1.05 m) which were commonly tested; these relationships may be employed to predict these parameters at large landing heights.

The range of peak GRF obtained in the current study was slightly lower compared to previous studies, [9–12,20–22] though the peak GRF data obtained among all these studies were quite varied. This may be explained by the type of landing style adopted by the different subjects in these studies. DeVita and Skelly [8] stated that a soft landing style produces a mitigated GRF compared to stiff landing. Moreover, it was previously reported that gymnasts who tend to land with minimal knee flexion incurred higher GRF than recreational athletes [10]. In our study, it was notable to observe a marked exponential relationship between peak resultant GRF and landing height.

In addition, we observed notable exponential regression relationship between peak GRF slope/impulse and landing height. Seegmiller and McCaw [10] reported a general rise in peak GRF impulse with landing height for recreational athletes, though a statistical significance was not detected; elevation in landing height can increase the exposure to high GRF magnitudes and loading rates, which are key contributing factors to injury. The presence of larger peak impact force and loading rate also indicated weaker shock-absorbing capacity, which may increase the susceptibility to lower-extremity overuse injuries [14,23]. Our observations established that the peak GRF, GRF slope and GRF impulse incurred during landing are highly dependent on landing height and these exponentially-elevated peak GRF parameters during landing from a great height can potentially heighten the risk of developing lower extremity injuries.

The knee flexion angles at initial contact and at peak GRF demonstrated inverse-exponential relationship with landing height. The gradual increase in knee flexion angles at both events with landing height up to 0.75 m may represent the inherent mechanism of the musculoskeletal system to increase knee flexion so as to provide enhanced shock absorption capacity against the elevated GRF [14,17]. However, at landing heights beyond 0.75 m, the knee flexion angles at initial contact and at peak GRF were found to increase at a slower rate. The reduced rate of increase observed in these knee flexion angles may contribute to diminished shock absorption in response to exponentially increasing peak GRF.

DeVita and Skelly [8] reported that a soft landing style leads to an attenuated GRF relative to stiff landing. Thus, the presence of lower knee flexion during stiff landing can lead to a diminished shock absorption capacity, whereby the articular cartilage will sustain large compressive impact loads [24] that can afflict cartilage lesions [14]. Yu et al. [25] previously demonstrated that the knee flexion angular velocity has a negative correlation with peak GRF during landing, which implied that active knee flexion is an important player in impact force attenuation. Furthermore, the presence of a negative knee joint power revealed eccentric work done on knee extensors to dissipate impact energy. Zhang et al. [19] reported that negative knee joint power increased with landing height, which suggested that the

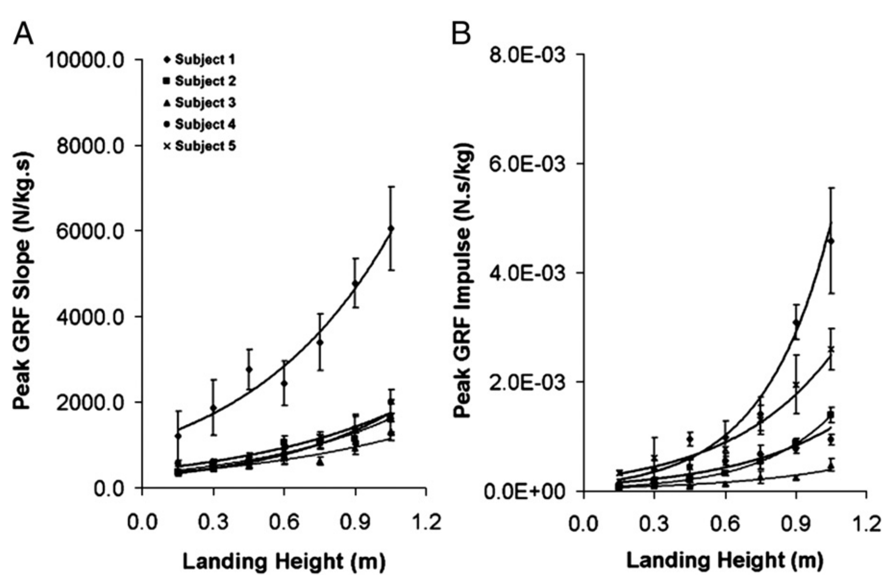

Fig. 3. Exponential regression relationships of landing height with (A) peak GRF slope and (B) peak GRF impulse for all subjects generally followed a $y = ae^{bx}$ equation, where y = peak GRF slope/impulse, x = landing height, a,b = regression coefficients.

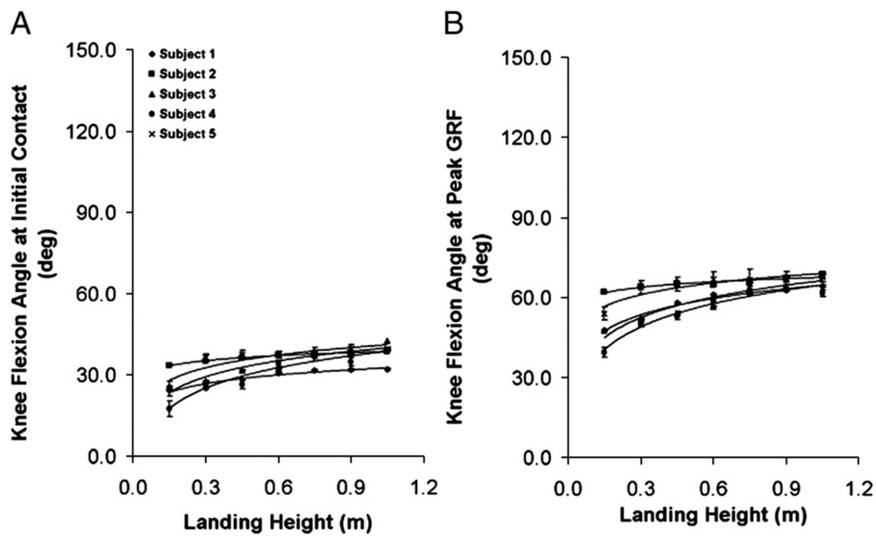

Fig. 4. Inverse-exponential regression relationships of landing height with knee flexion angles (A) at initial contact and (B) at peak GRF for all subjects generally followed a $y = a\ln(x) + b$ equation, where y = knee flexion angles at initial contact/at peak GRF, x = landing height, a,b = regression coefficients.

knee extensors were vital contributors to energy dissipation. Additionally, in our study, we noted an inverse-exponential relationship between knee flexion angular velocity and landing height, and a simple linear relationship between knee joint power and landing height. Altogether, these findings suggested that the energy dissipation capacity of the knee joint increased at a relatively slower rate at higher landing heights despite the exponentially-increasing GRF parameters. This 'misbalance' between energy dissipation capacity and GRF parameters at great landing heights is likely to aggravate lower extremity injury risk.

One key limitation of our study is the progressive conduct of the landing tasks with regards to the landing height. We expect that potential injury risks may exist in randomized landing trials; for instance, if the subjects were to perform the landing trials with greater height (0.90–1.05 m) initially, there is a higher tendency for injury compared to having the landing trials with lower height (0.15–0.30 m) conducted first. Though the findings of this study may not be completely reflective of the actual landing condition wherein an athlete lands from a large height in a single task, we identified a benefit in this progressive landing protocol as it helps the subjects to attune to the landing style that best facilitates them in shock attenuation.

Another limitation is perhaps the potential inter-subject differences in landing style, which may influence the regression relationships obtained for each subject between the dependent and independent variables. Although we did not specifically instruct the subjects to follow a standardized landing style, our qualitative examination of their landing motions revealed mostly 'soft' landing styles which may explain the lower peak GRF obtained compared to previous studies. Since we are more concerned with investigating the effect of landing height on GRF, knee flexion angles, angular velocities and joint powers for recreational athletes who have different landing experiences, we permitted the subjects to execute their natural landing styles. Setting a standardized landing style for all subjects may introduce confounding variables such as the individual ability in learning the landing style; a standardized landing style would be more relevant for studies on specific groups of athletes, such as gymnasts and volleyball players, who would possess similar levels of learning ability and landing experience.

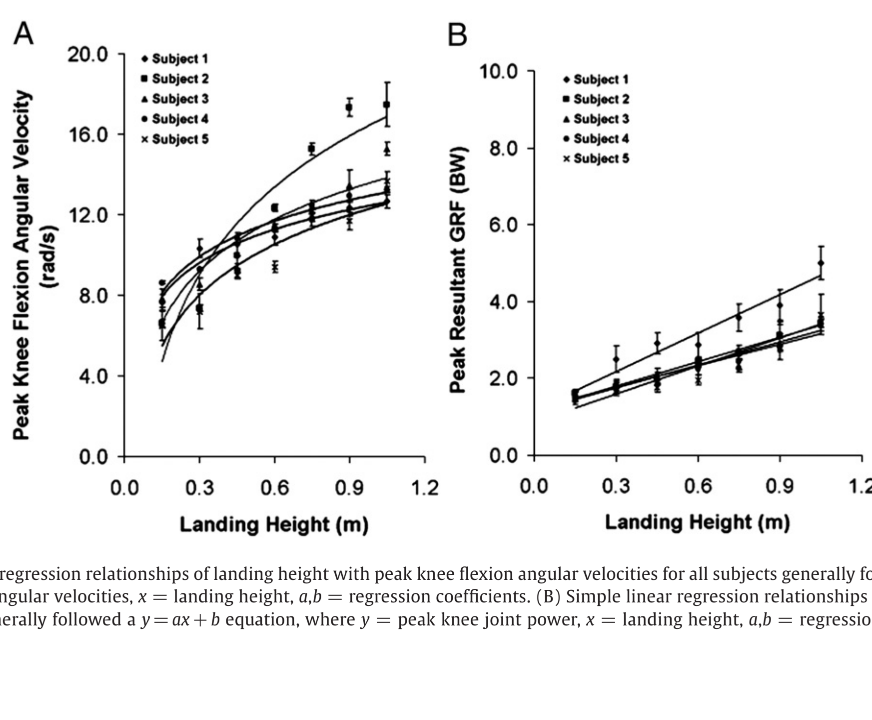

Fig. 5. (A) Inverse-exponential regression relationships of landing height with peak knee flexion angular velocities for all subjects generally followed a $y = a\ln(x) + b$ equation, where y = peak knee flexion angular velocities, x = landing height, a,b = regression coefficients. (B) Simple linear regression relationships of landing height with peak knee joint power for all subjects generally followed a $y = ax + b$ equation, where y = peak knee joint power, x = landing height, a,b = regression coefficients.

We acknowledged that the study was constrained by a small sample size, hence our results may not be representative of the general population. However, our post-hoc power analysis revealed that there was generally a sufficiently high power to detect the observed regression relationships in the data obtained in our study. While we cannot conclude the general population would follow these regression relationships during landing, we were able to show that the relationships have a strong fit in terms of R^2 and p values for the 5 subjects tested in our study. In addition, there are certain factors in a physiological landing task specific to a sports-/military-related setting, like upper body motion, friction/gradient of landing surface, type of shoe/boots worn, additional carried weights and post-landing maneuvers, which are not examined in the current study. These factors may usually cause unexpected effects on the landing biomechanics of the athlete and elevate injury risk [1]. Since we intended to investigate the regression relationships of landing height with GRF, knee flexion angles, angular velocities and joint powers, it is therefore necessary to conduct the present study in a controlled laboratory environment so that the subjects knew exactly what to expect and can perform the same sets of landing tasks with minimal injury risk.

Our results collectively established that the peak resultant GRF, GRF slope and GRF impulse possessed strong exponential regression relationships with landing height, while knee flexion angles (at initial contact and peak GRF) and peak knee flexion angular velocities followed an inverse-exponential relationship with landing height, and peak knee joint power adopted a simple linear regression relationship with landing height. The parameters analyzed in this study are highly dependent on landing height. The exponential increase in peak GRF parameters and the relatively slower increase in knee flexion angles, angular velocities and joint power may synergistically lead to an exacerbated lower extremity injury risk at large landing heights.

5. Conflict of Interest

We declare that there are no direct or indirect financial interests involved with the content of this paper. The main source of grant support for the project is the Academic Research Fund (National University of Singapore). The project is also co-supported by the Defence Medical and Environmental Research Institute.

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