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DYNAMIC FORCE RESPONSE OF HUMAN LEGS DUE TO VERTICAL JUMPS

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ABSTRACT

Jumping is a natural exertion that occurs during a variety of human activities including playing sports, working, skateboarding, dancing, escaping from hazardous events, rescue activities, and many others. During jumping, the ankles in particular are expected to support the entire body weight of the jumper and that may lead to ankle injuries. Each year hundreds of patients are treated for ankle sprains/strains with ankle fractures as one of the most common injuries treated by orthopedists and podiatrists. The knee joint is also considered the most-often injured joint in the entire human body. Although the general anatomy of the lower extremities is fairly well understood, an understanding of the injury mechanism during these jumping tasks is not well understood. The aim of this study is to determine the reaction forces exerted on legs and joints due to vertical jumps, through musculoskeletal simulation and experimental studies to better understand the dynamic jump process and the injury mechanism. The joint reaction forces and moments exerted on the ankle, knee and hip joint during takeoff and extreme squat landing of a vertical jump were determined through the application of musculoskeletal simulation. It is concluded that during extreme squat landing of a vertical jump, joint reaction forces and moments were highest in proximal/distal and anteroposterior direction may cause most likely injury to the hip joint ligaments, ankle fracture and knee joint, respectively.

INRODUCTION

There are different types of jumps that may occur depending on various situations. Several types of jumps with unique kinematics have been described and include the- vertical jump, squat jump, vertical leap, long jump, and stop jump [1-5]. These kinds of jumps mostly occur while playing a verity of sports like basketball, volleyball, soccer, football, and gymnastics [1]. The jumping ability of an athlete is also an indicator of overall athletic ability, as there is a clear relationship between the ability to jump and the running speed that the athlete will develop over short distances [1]. Moreover, jumping phenomena occurs while escaping from the hazardous events such one has to jump from a balcony of a house to escape from the fire.

Jumping has been considered as one of the most complex motions of the human body and a potential cause injury to the lower leg extremities.

The lower leg anatomy can be modeled as consisting of thigh, shank and foot segments connected through hip, knee and ankle joints respectively. No portion of the lower leg anatomy is capable of independent physical action [7]. The hip, knee and ankle joint play a major role while performing a jump task.

Improper jumping such as those taking place in sports activities may cause an injury due to impact forces exerted on legs [1]. Generally sport injuries may occur due to accident, poor training, excessive loading, improper equipment and insufficient warm-up [1]. Although injury could occur in any part of the body during the jump, the term here stands for injuries at lower extremities of the human body. Sprain or tear of the ligaments, the band of connective tissues that joins the end of one bone with another [1]. Medical professional and scientists have often associated the impact shock of jump landing with various knee injuries, including tendinosis, Anterior Cruciate Ligament (ACL) injury, and osteoarthritis [2]. However, it is not known to what extent excessive impact forces, abnormal anatomy, or altered kinematics may contribute to injury [2].

The magnitude of the forces exerted on legs due to vertical jump was studied by several researchers [2-5]. Various experimental approaches have been applied to understand the dynamics of vertical jump process. Fadi and John [3] in their study 'Impact Forces During Exit From Commercial Vehicles Study' investigates the maximum forces exerted on legs during of exiting commercial tractors, trailers and trucks. The results of this study showed that exiting from cab-level or trailer-level resulted in impact forces as high as twelve (12) times the subject's body weight; whereas, fully utilizing the steps and grab-rails on the vehicle resulted in impact forces less than two (2) times body weight of the subject. The impact forces were measured by a 3-dimensional forceplate as shown in the experimental setup of Figure 1.

Figure 1- Forceplate setup for exiting from conventional tractor cabin [2].

Athanasios and Adrian [4] in their paper 'A Biomechanical Analysis of Good and Poor Performers of the Vertical Jump' investigated muscle strength capabilities and the technique used by good and poor performers of the vertical jump. They concluded that the muscle strength characteristics of the lower limb joints are the main determinant of the vertical jump performance with technique playing a smaller role. And to come up with that conclusion Vanezis and Lees have explained the dynamics of the vertical jump by distinguishing it in terms of kinetics and kinematics.

Bing, Cheng-Feng and William [5] carried out a study 'Lower Extremity Biomechanics During the Landing of a Stop-jump Task', to examine the relationships among selected lower extremity kinematics and kinetics during the landing of a stop-jump task. This study examines that landings with great impact forces may be a risk factor for knee injuries, especially Anterior Cruciate Ligament (ACL) tear. Authors of this study concluded that a large hip and knee flexion angles at the initial foot contact with the ground do not necessarily reduce the impact forces during the landing of the stop-jump task, but active hip and knee flexion do. Furthermore, the hip joint motion at the initial foot contact with the ground appears to be an important technical factor that affects anterior cruciate ligament loading during the landing of the stop-jump task.

In general, the research conducted on biomechanics of a jump and landing is to determine the biomechanical factors that could minimize the impact of forces on joints in the human body. The previous research studies can be helpful to prepare experimental setup for data collection. Musculoskeletal simulation was carried out in this study to further quantify the combined kinetics and kinematics of lower extremities during jumping and identify how this technique can be used to improve our understanding of injury mechanism during jumping and landing. The objective of this study is to determine the reaction forces exerted on legs and joints due to a vertical jump and to compare these forces with those that could be a risk factor for damage to bones and joints through the application of musculoskeletal simulation.

METHODOLOGY

A musculoskeletal computer simulation is used to determine the joint reaction forces and moments exerted on the legs during a vertical jump and landing. Kinematics and kinetics data of a vertical jump were collected using 3D-Motion capture and ground reaction force analysis. The effect of the jump and landing kinematics on the internal body joint forces was analyzed by musculoskeletal modeling of the vertical jump motion using the AnyBody Modeling System musculoskeletal simulation software [6]. The details of the methodology were submitted and approved by Institutional Review Board (IRB) at San Jose State University and informed consent was provided by participant.

ANALYSIS

Kinematics defines the range of motion and describes the surface motion of a joint in three planes: frontal (coronal or longitudinal), sagittal, and transverse (horizontal). In the knee and hip joint, motion takes place in all three planes, but the range of motion is greatest by far in the sagittal plane. Motion in this plane from full flexion of the knee and hip is from 0° to approximately 140°. For the ankle joint measurements yield a normal motion of 10° to 20° dorsiflexion and 40° to 55° plantarflexion [7].

Kinetics involves both static and dynamic analyses of the forces and moments acting on a joint. Static is the study of the forces and moments acting on body in equilibrium, for which, sum of the forces is zero and sum of the moment is zero. Dynamics is the study of the moments and forces acting on a body in motion (an accelerating or decelerating body). Kinetics analysis allows one to determine the magnitude of the moments and forces on a joint produced by body weight, muscle action, soft tissue resistance, and external forces in any situation [7]. The reaction force supplied by the ground is specifically called Ground Reaction Force (GRF) [8]. According to Newton's third law of motion, for every action there is an equal and opposite reaction; due to gravity interaction between ground and the body causes the reaction forces in joints [8].

EXPERIMENTAL WORK

Human motion data collection is required to capture kinematics of a vertical jump. Data collection includes forceplate data, video capture of a vertical jump motion and digitizing of markers attached to the body. In this study Vicon Motus System [9] was used for human motion data collection in the Department of Kinesiology, Bio-mechanics Laboratory at San Jose State University. Two different vertical jumps motion data were captured. The first one is a vertical squat jump and the second is a vertical jump from a certain height.

One subject aged of 25 years participated in this study. Subject had average body type and 130 lb body weight. In the first case the participant jumped from a stationary posture with both feet on each force plate fixed on the ground as high as he could, and land with both feet in approximately the same place as at the start of the jump. In second case participant jumped from a height 1.25 m (~ 4 ft) and landed with both feet on each forceplate fixed on the ground. In the second case jump height was selected for a jump from the cab of a tractor, 1.25 m as studied previously by Fathallah et al. [2]. Participant was allowed as many practice jumps as necessary to gain familiarity and to become comfortable with the testing apparatus. Once the participant was comfortable with a selected jumping strategy, video capture has been collected while the participant performed a maximum of 5 jump trials for both cases. Each jump trial lasted approximately 6 seconds which included a push off from the ground, vertical flight travel, and landing, in first case and push off from a height, flight travel and landing, in second case.

EQUIPMENT USED FOR DATA COLLECTION

One inch diameter retro-reflective markers, tight fitting clothes, double sided adhesive tape [10], four cameras (Canon) [11], four bulbs light, two force plates (Kistler) [12], and two computers were used in the experimental setup. The one-inch diameter retro-reflective markers were attached with a double-sided adhesive tape at the following locations: front head, right and left acromion, sternum top and bottom, right and left lateral epicondyle of the humerus, right and left wrist, right and left Posterior points of the pelvis (PSIS), right and left lateral epicondyle of the femur, right and left ankle, right and left foot medial and lateral; these marker placements are with reference to those used by Wagner [13, 14].

A calibration frame containing 24 points with known 3D locations was recorded by four video cameras at the beginning of each testing day as shown in Figure 2. The video cameras recorded 60 pictures per second and had an exposure time of 1/2000 of a second per picture. 24 points are used during data analysis to determine three-dimensional coordinates of attached reflective markers.Two force plates as shown in Figure 2, synchronized in-line with each other were used for jumping and landing from a stationary posture with both feet on each force plate in first case and the same were used for landing only in second case. Force plate analog signals sampled at

Figure 2- laboratory set up including a Calibration Frame with 24 Points and Two Force Plates

1000Hz [13]. The captured force plate data and 3D-coordinates of vertical jumps were exported in excel format from Vicon Motus System. The text format of exported files was used as an input for musculoskeletal modeling.

Figures 3 and 4 shows, the Ground Reaction Forces (GRF) in Newton measured by two force plates in the X direction, which represents anterior/posterior forces, in the Y direction which represents vertical forces and in Z direction, which represents the medial/lateral forces. As the jump kinematics was primarily in the vertical direction, we expect the magnitude of the forces in the X and Z directions to be significantly lower than the vertical forces. However, that was not the case and it is expected crosstalk between the signals occurred and only the vertical forces were considered for the musculoskeletal simulation. The magnitude of forces in Y direction shows the ground forces exerted on legs for takeoff and landing cases. The peak ground reaction force of 1381 N and 1758 N in Y direction were observed as results of vertical squat jump and vertical landing from a height, respectively.

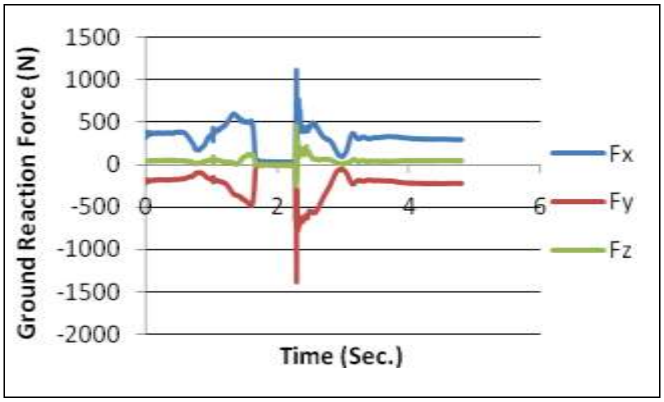


Figure 3- Ground Reaction Force (GRF) exerted on legs due to a vertical squat jump.

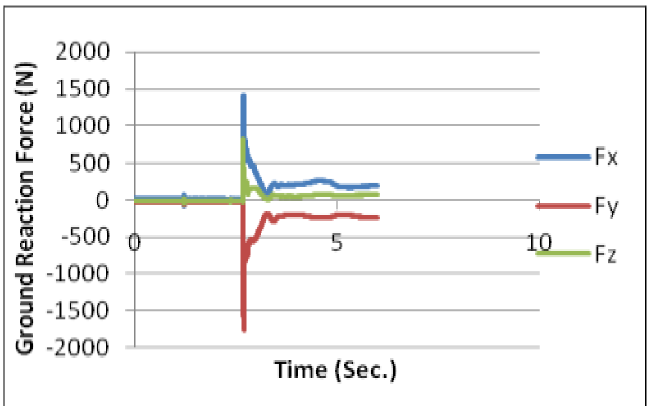


Figure 4- Ground Reaction Force (GRF) exerted on legs due to a vertical landing from a height.

SIMULATION

Musculoskeletal simulation was carried out using the AnyBody Musculoskeletal System. AnyBody software works on the principle of Inverse Dynamics requiring as input motion and boundary forces [15]. In order to perform an inverse dynamics rigid body (segments), joints, motion and external forces are required. The human body is modeled as a series of rigid bodies with idealized joints (i.e. spherical for the hip joint) is used to model the joints of the human body. Muscle lines of action and properties were defined by the AnyBody system and scaled to match the anthropometry of the participant being modeled. Ground reaction force data were used assuming both feet to leave and reach back on the forceplate together at the same moment during takeoff and landing.

RESULTS AND DISCUSSION

Lower legs joint reaction forces that are exerted during take-off and landing have been calculated using AnyBody simulation software for the vertical squat jump. Joint reaction forces and moments are calculated for three particular instances such as during takeoff, initial impact and extreme landing squat position. During takeoff the joint reaction forces/moments calculated at time step 1.116 second as shown in the Figure 5. Figures 6 and 7 show the initial impact and the extreme squatting position followed the landing process, at the time steps 2.0378 and 2.2904 second, respectively.

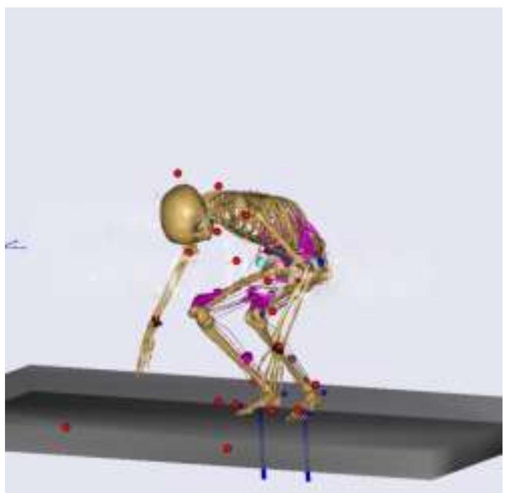


Figure 5- Take off position at the time step 1.116 second.

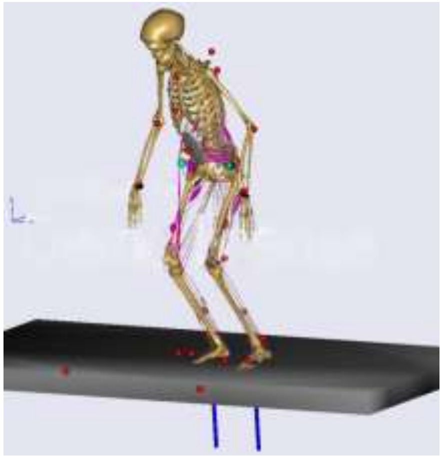


Figure 6- Near Impact position at the time step 2.0378 second.

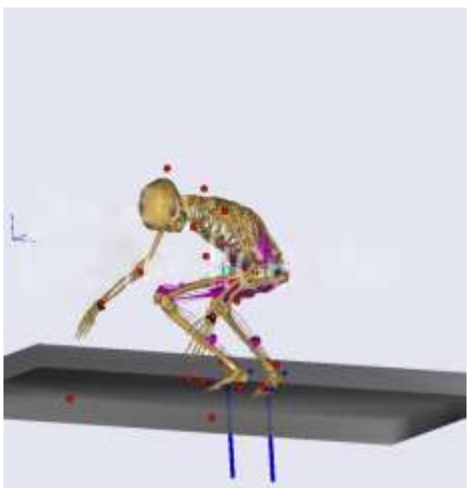
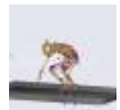
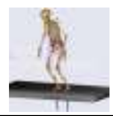


Figure 7- During Extreme Squat Landing position at the time step 2.2904 second.

Table 1 shows the calculated values of joint reaction forces exerted on each joint in three directions at take off, initial impact and during extreme landing squat. During squat landing, a joint reaction force 5,717 N on knee joint is exerted equivalent to 4 times peak GRF and 3,650 N on ankle joint equivalent to 2.7 times peak GRF. The highest level of joint reaction force 9,768 N which is equivalent to seven times peak GRF, exerted on the hip joint in proximal/distal direction during extreme landing squat of a vertical jump. The highest magnitude of anteroposterior reaction force 13,318 N exerted on the knee joint during extreme squat landing is equivalent to 9.5 times peak GRF.

Table 1- Summary of calculated joint reaction forces exerted on right leg joints

	During take off		
	Ankle	Knee	Hip
Mediolateral(z) Force(N)	-23	226	-2883
Proximodistal(y) Force (N)	-2,724	1,265	6,975
Anteroposterior(x) Force (N)	380	-7,635	1,087
Axial Moment (N.m)	0.51	127	NA
Lateral Moment (N.m)	NA	-25	NA
	Initial Impact		
	Ankle	Knee	Hip
Mediolateral(z) Force(N)	-27	-57	-1404
Proximodistal(y) Force (N)	-2,889	-1,448	2,891
Anteroposterior(x) Force (N)	364	-2,986	351
Axial Moment (N.m)	0.33	48	NA
Lateral Moment (N.m)	NA	-43	NA
	Extreme squat landing		
	Ankle	Knee	Hip
Mediolateral(z) Force(N)	30	191	-3,477
Proximodistal(y) Force (N)	-3,650	5,717	9,769
Anteroposterior(x) Force (N)	576	-13,318	1,549
Axial Moment (N.m)	-4	153	NA
Lateral Moment (N.m)	NA	-98	NA

From Table 1, it is noted that the hip joint proximal/distal reaction force is higher than that occurred on knee and ankle joints. This is in agreement data presented by Paul et. al. (1970), which calculated the magnitude of peak joint reaction force occurred on the hip joint was five to seven times that of body weight and the largest in magnitude between the ankle and knee joints [7]. Axial and lateral moment occurs on knee joint with respect to extension and abduction on the knee, which is higher during extreme landing squat. Knee extension moment may contribute to the knee joint injury while knee abduction moment is not associated with any of the injury risk factors. This also is in agreement with risk factors and mechanism of knee injury research study by Stephen and Claudine [16] found that larger knee joint loads were related to poor hamstring flexibility, higher body weight and greater muscular strength. A Recent analysis of the National Automotive Sampling System (NASS) database indicates that the current knee-thigh-hip (KTH) injury criterion is 10,000 N peak femur forces, which is based on the fracture tolerance of the femur to high-rate axial loading applied at knee. Klopp G. [17] also has shown that 50% probability of injury to the planter side of the ankle could occur at 9,300 N contact force. According to Atlanta sports medicine on Anterior Cruciate Ligament (ACL) injury, 'Criteria for Return to Play' for an athlete may cause residual pain or neuromuscular deficiency in ACL as the criteria includes an athlete should be able to perform three successive vertical jumps with high repeatability of their median maximum jump. Anteroposterior joint reaction force acting on knee joint could be the risk factor for ACL injury to knee joint [18]. Hip injury is a major concern because they account for a large number of life years lost from injury to knee-thigh-hip (KTH) according to an article published by the National Highway Traffic Safety Administration (NHTSA) authored by Jonathan, Mathew and Nathaniel [19]. Other than the applied external forces, muscle forces have greatest influence on the magnitude of the joint reaction force [7]. Phil Sadler [20], in his research on hip and pelvis joint reported that strength, stability and mobility occur through the hip and pelvis because of strong support from muscles of the trunk and muscles of the lower limbs, allowing forces to transfer between upper and lower extremities.

CONCLUSIONS

This study provides significant information on biomechanical analysis of dynamic vertical jump through the application of a musculoskeletal simulation. Kinetics and kinematics of vertical jumps were collected using experimental methods. In this study, if the same kinematics were used with the increased kinetics, it may cause an injury to the hip joint ligaments first, due to highest joint reaction forces were exerted in proximal/distal direction during takeoff, at initial impact and extreme squat landing positions. On the knee joint, during extreme squat landing the highest joint reaction force was exerted in the anteroposterior direction, which could cause anterior cruciate ligaments tear. The greater amount of proximodistal forces were exerted on the ankle joint during initial impact and extreme squat landing may cause an ankle fracture. However, dynamics of the leg joints injury mechanism during jumping phenomena depends on subject's jumping task, body type and body weight. Kinematics of a digital human model used in this study can be analyzed to determine muscle reaction forces exerted on leg joints for further analysis through the application of the musculoskeletal simulation.

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