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Real-Time Measurement of Rectus Femoris Muscle Kinematics during Drop Jump using Ultrasound Imaging: A Preliminary Study

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Abstract— **We have developed an office based vector tissue Doppler imaging (vTDI) that can be used to quantitatively measure muscle kinematics using ultrasound. The goal of this preliminary study was to investigate if vTDI measures are repeatable and can be used robustly to measure and understand the kinematics of the *rectus femoris* muscle during a drop jump task. Data were collected from 8 healthy volunteers. Vector TDI along with a high speed camera video was used to better understand the dynamics of the drop jump. Our results indicate that the peak resultant vector velocity of the *rectus femoris* immediately following landing was repeatable across trials (intraclass correlation coefficient=0.9).The peak velocity had a relatively narrow range in 6 out of 8 subjects (48-62 cm/s), while in the remaining two subjects it exceeded 70 cm/s. The entire drop jump lasted for 1.45 $\pm$ 0.27 seconds. The waveform of muscle velocity could be used to identify different phases of the jump. Also, the movement of the ultrasound transducer holder was minimal with peak deflection of 0.91$\pm$0.54 degrees over all trials. Vector TDI can be implemented in a clinical setting using an ultrasound system with a research interface to better understand the muscle kinematics in patients with ACL injuries.**

Keywords-Ultrasonography; vector Doppler; tissue motion; drop jump; anterior cruciate ligament injury; osteoarthritis; musculoskeletal imaging; signal processing; muscle motion

I. Introduction

ANTERIOR cruciate ligament (ACL) tear in the knee is one of the most common musculoskeletal injuries [1]. Athletes who are involved in intense pivoting activities are at higher risk of ACL injury [2]. ACL injuries have significant public health implications as it takes a long time to rehabilitate, presents high costs, and often leads to long-term morbidity. There is a high prevalence of knee osteoarthritis (OA) post ACL injuries [3] with 45% to 70% of individuals presenting early onset of OA [4]. Early onset of OA in young individuals may result in adverse health conditions and could limit activities of daily life (ADL). Although, ACL injuries are highly prevalent, the underlying musculoskeletal mechanisms that lead to OA are poorly understood.

Quantitative measurements of muscle kinematics and function can enhance the understanding of the contributing factors leading to the early onset of OA. Conventionally, joint kinematics and kinetics using 3D motion capture systems, ground reaction force and electromyography are used to understand the change in gait in these patients. Studies using 3D motion capture systems have shown increased frontal plane knee adduction moment during gait [5], and sagittal and transverse plane knee movements during drop jumps [6]. Others have also shown a possible relationship between quadriceps weakness and knee OA in all knee joint compartments [7]. Recently, muscle morphology during static trials using magnetic resonance (MR) imaging has also been studied [8]. However, the underlying muscle kinematics preventing adequate joint protection during dynamic tasks following ACL reconstruction remains poorly understood.

Ultrasound imaging is an attractive alternative for measuring musculoskeletal dynamics and function during dynamic tasks, because it can enable direct measurement of muscle kinematics. Concurrently quantifying biomechanics and muscle function during dynamic activities can provide a unique opportunity to elucidate the mechanisms leading to early onset of OA post ACL injury. Previously, real-time B-mode ultrasound has been used for dynamic imaging of *gastrocnemius* muscle motion [9-10]. These methods are not suitable to measure fast contraction velocities during highly dynamic tasks (e.g., drop jumps) that maximally load the knee joint. A spectral Doppler ultrasound method could be suitable for fast moving scatterers; however, conventional duplex Doppler is angle-dependent and would introduce errors in measuring muscle velocities due to continuous changes in insonation angle throughout the contraction-relaxation phase of the muscle during dynamic tasks. This problem can be overcome by estimating the velocity of the object using two different ultrasound beams steered at different angles, a method known as vector Doppler. We have previously developed vector tissue Doppler imaging (vTDI) to quantitatively measure tendon and muscle kinematics *in-vivo* during dynamic tasks [11-12].

To investigate the repeatability and potential applicability to ACL deficient individuals of the vTDI system in measuring musculoskeletal velocities, we

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performed a preliminary study on healthy adult volunteers. The goal of this paper was to investigate if the vTDI measures are repeatable and can be used for understanding the contraction velocity of the *rectus femoris* muscle in real time during drop jump.

II. Methods and Materials

A. Participants

Eight (N = 8) healthy volunteers (4 men and 4 women; age = 29.7 ± 6.5 years) were recruited and provided informed consent approved by our Institutional Review Board. The exclusion criteria were previous diagnosis of neuromuscular disease, knee pathology or previous knee surgery.

B. Data Acquisition Procedures

All subjects were asked to perform a natural drop jump from a platform at a height of 26 cm with their hands on their hips and land simultaneously on both legs. Ultrasonix Sonix RP® US system (Richmond, BC, Canada) with a 5-14 MHz linear array transducer was used for imaging. The ultrasound transducer was secured in place using a custom holder made with lexen polycarbonate and moldable plastic and held using cohesive flexible bandage while allowing full knee extension and flexion during jump (Fig. 1). B-mode imaging was used to ensure that the center of the *rectus femoris* muscle was located at the center of the expected beam overlap region. Vector Doppler imaging was performed as the subject executed the jump and data were collected from the *rectus femoris* muscle in real time with an effective temporal resolution of at least 0.12 ms. A Photron 512 PCI 32K high speed camera (Photron, CA, USA) mounted on a tripod and placed at 2 m from the subject, was used to capture the drop jump at 500 frames/s. Visible markers were placed on the trochanter, mid-thigh and the lateral epicondyle, as well as on the ultrasound transducer to evaluate relative motion between the transducer and skin. The procedure was repeated twice for each subject.

C. Vector Tissue Doppler Imaging

Vector TDI estimates velocity components of the *rectus femoris* muscle, based on measurements taken from two or more independent directions by electronically splitting an array transducer into multiple apertures. Our previous work [11-12] details the implementation of vTDI. Briefly, a 5-14 MHz linear array transducer with 38mm field of view was used. The transmit and receive beams are steered at 15° with respect to the normal and the respective apertures were set to 32 elements. Velocity estimation was done using 2D Fourier transform described previously [13].

D. High Speed Camera Data Processing

Post processing of the high-speed video was done using Photron Fast Cam Viewer (Photron, CA, USA). The software was used to play the recorded movie at 15 frames per second to quantify the movement of the transducer holder and the displacement of the ultrasound probe during drop jump, and assess the dynamics of the jump.

E. vTDI and High Speed Camera Data Analysis

The contraction velocity waveforms of the muscle along the axial and lateral directions of the transducer were obtained from the vTDI data. The peak magnitude of the resultant velocity vector was obtained from axial and lateral velocity waveforms. The video was then compared to the velocity waveform obtained using vTDI and manually synced at the instant when the subject started the flexion for launch (beginning the jump). The peak resultant velocity just after the landing phase (heel strike) of the jump was calculated.

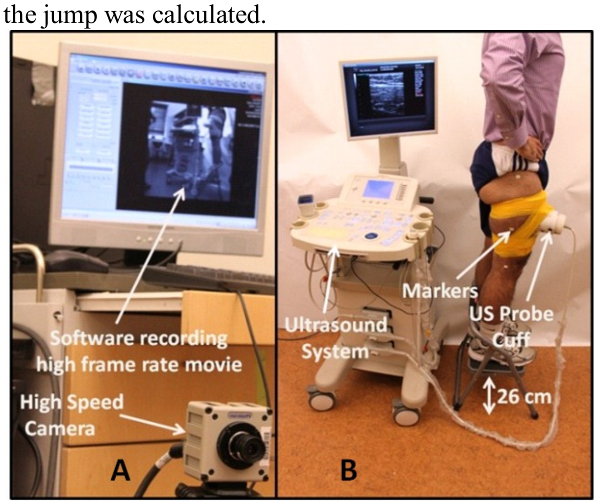

Figure 1. The experimental setup for measuring the *rectus femoris* muscle velocities during drop jump. Panel A consists of a high speed camera and a computer to record videos. Panel B shows a subject on a platform and a US transducer on the *rectus femoris* held in place using a custom built holder and strapped using a flexible bandage. Visible markers were places on anatomical landmarks.

F. Statistical Analysis

Intraclass correlation was performed using PASW 18 (IBM Corporation, NY, USA) for magnitude of the resultant velocity vector and the displacement of the ultrasound probe during drop jump was done over all 16 trials. Analysis of co-variance (ANCOVA) was performed with weight and muscle thickness as co-variables to investigate any gender differences in muscle velocity.

III. Results

Axial and lateral muscle velocities were compared with the dynamics of the drop jump using high frame rate videos. During each trial, the pattern of subject's jump, landing and stabilization were studied.

Fig. 2 represents the frames of the high-speed video and the time series of axial and lateral muscle velocities obtained using vTDI, corresponding to the entire drop jump trial. The entire drop jump sequence lasted approximately 1.45 ± 0.27 seconds.

The axial and lateral velocity values showed a strong repeatability between trials for each subject, with a slope of 0.99 and R^2 = 0.75 (Fig. 3). Six out of eight subjects presented similar velocity values in the range of 48-62 cm/s, while two subjects (both men) had higher velocities. There was also a statistically significant difference in muscle velocity between men and women. When adjusting for each individual weight and muscle thickness, males (72.96 cm/s) presented significantly higher muscle velocity than females (48.71 cm/s), p=0.029. The resultant muscle velocity, as expected, demonstrated high repeatability ($ICC_{2,1}$ = 0.907, $p<0.05$).

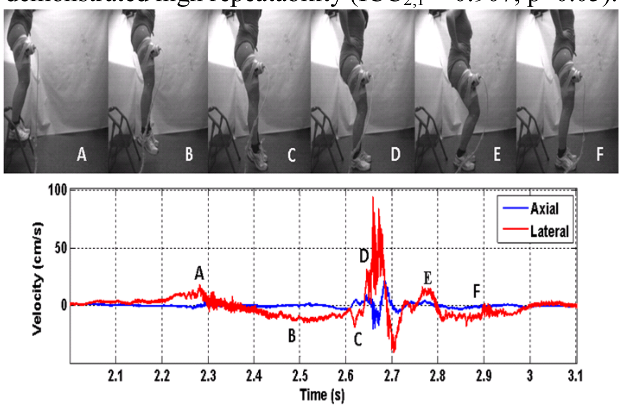

Figure 2. Axial and Lateral velocities during drop jump are compared to the sequence of video frames (upper panel). The lower panel is the axial and lateral velocities, where A corresponds to the initial knee flexion, B corresponds to the knee extension, C corresponds to the toe striking the ground, D corresponds to the heel striking the ground, E corresponds to knee flexion post landing and F corresponds to the knee extension and stabilization.

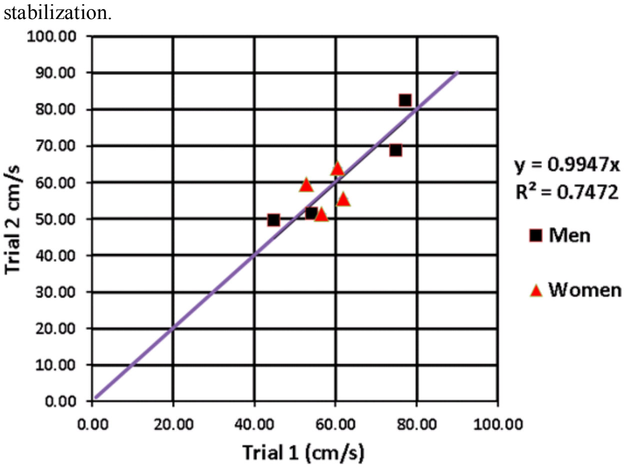

Figure 3. Repeatability of the magnitude of the resultant velocity vector for all 8 subjects (2 trials per subject). Men are denoted in black squares and women in red triangles.

The high-speed camera was used to track the movement of the ultrasound transducer holder during landing phase of the drop jump. The angle between the line segment made between the trochanter and the cuff (black line segment) and the line segment between the mid thigh and the cuff (red line segment) was calculated for all 16 trials (Fig. 4). We observed minimal angular variation (0.91 ± 0.54 degrees) of the transducer holder relative to the anatomical markers during landing (Fig. 5). The ultrasound transducer angular variation presented a high repeatability as well ($ICC_{2,1}$=0.90, $p<0.05$).This confirmed that the probe movement was minimal during the jump and the velocity measurements were not affected.

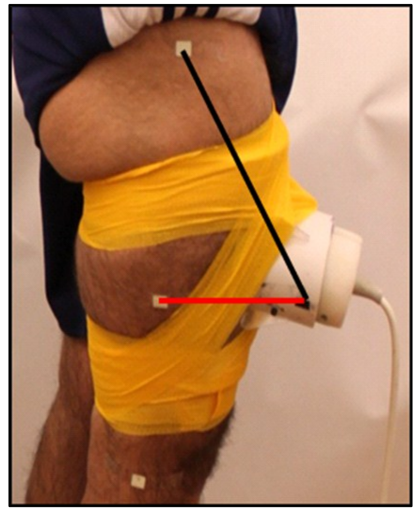

Figure 4. The error in the angle between the line segment made by ultrasound transducer holder and the marker on the mid thigh (red line segment) and the line segment made by the ultrasound transducer and the marker on the trochanter (black line segment).

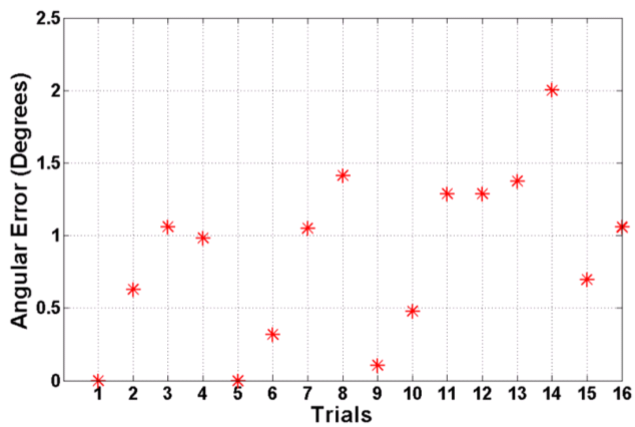

Figure 5. The absolute error in the angle between the line segment made by ultrasound transducer holder and the marker on the mid thigh and the line segment made by the ultrasound transducer and the marker on the trochanter.

IV. DISCUSSION

In this study we investigated the repeatability of the *rectus femoris* muscle kinematics during a drop jump task in eight healthy volunteers using vTDI. We observed highly correlated and repeatable peak contraction velocities for individuals between trials, in spite of the trials being independent. Our preliminary results indicate possible differences in muscle velocity between men and women. We will recruit more volunteers in our study to further examine this pattern.

Our experiment has shed some light on *rectus femoris* muscle velocity during a drop jump. The main findings are: 1. Muscle contraction velocities dominate in the lateral direction compared to axial direction during the knee flexion (launch phase) and extension (in-the-air phase). 2. Low lateral muscle velocities during the third phase (toe touching the ground), with negligibly low axial muscle velocities. 3. Substantial increase in axial and lateral muscle velocities just after the heel touches the ground. This is probably due to the muscle undergoing both contraction and change in shape due to compression, causing increase in axial velocities. Despite this fact, the vTDI presented highly repeatable *rectus femoris* muscle velocity. This has useful clinical impact as this muscle is primarily responsible to protect the knee joint from excessive loads. Therefore, further assessment of this muscle in ACL deficient knees is warranted to understand the mechanisms leading to the early onset of OA.

Although preliminary, it appears that women have lower muscle velocity than men even after adjusting for potential weight and muscle thickness differences, studies focused on ACL injury rates and OA development should evaluate muscle function, and adjust for weight, muscle thickness and cross sectional area differences between subjects. The ability to effectively produce muscular force is directly dependent on the ability to quickly contact the muscle, in particular the *rectus femoris*.

All subjects were asked to perform a natural drop jump from a 26 cm high platform. However, the height of the jump or launch was different between subjects. The landing pattern of all the subjects across trials were carefully analyzed using the high-speed camera. It was observed that all the subjects had a different landing style on the ground (Fig. 6).

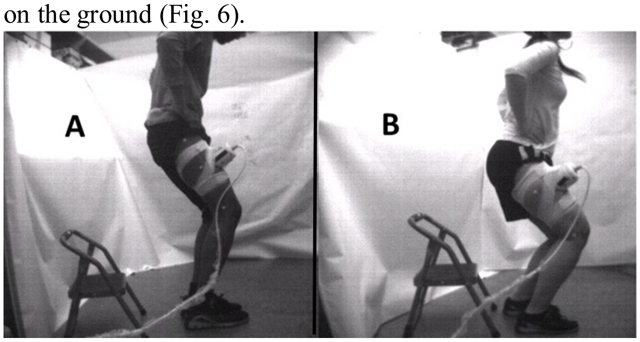

Figure 6. Figures in panel A and B show two subjects with two different styles of landing. In panel A subject's knee flexion in the landing phase is much lesser than the knee flexion of subject in panel B.

From Fig. 6, it is clear that the landing styles of subjects are unique. This could explain the marginally different peak velocity values of the *rectus femoris* muscle as a consequence of possible differences in activation patterns. However, in this small sample, we did not observe a significant correlation between knee flexion angle at landing and peak contraction velocity. Another possible factor is the differences in cross-sectional area of the *rectus femoris* muscle leading to different levels of contraction.

In this preliminary study, we used a high-speed camera to track the jump and probe motion. In future studies, we plan to integrate the ultrasound with a 3D motion tracking system, force plates and electromyography system to measure knee kinematics and kinetics. In future, vTDI measures at multiple locations along the muscle could be used to estimate additional quantities such as strain and strain rate. By combining muscle kinematics and activation patterns with concurrent assessment of joint kinematics and kinetics could provide further information into the contributing factors underlying the pathogenesis of OA after ACL reconstruction.

V. CONCLUSION

Our preliminary results demonstrate the feasibility of using ultrasound imaging in real time to quantitatively assess muscle kinematics during a dynamic task. This novel method provides direct assessment of muscle kinematics in dynamic studies that can complement conventional clinical outcome measures and can be broadly applicable for fundamental biomechanics research.

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