Technical note

A Device for Inducing Active Lengthening Muscle Contractions for Dynamic MR Imaging

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Abstract:

Acute muscle injuries and re-injuries are linked with active lengthening contractions. Dynamic imaging of in vivo muscle mechanics during lengthening contractions could provide new insights into injury mechanisms, and an assessment of how post-injury remodeling may contribute to re-injury risk. We have developed a MR compatible device that will inertially load the hamstrings in a manner similar to that seen during the swing phase of running, when that muscle is susceptible to injury. The device is non-ferrous, fits within the bore of a standard MRI machine and allow for a flexible MR coil to be placed around the fixed thigh. A compact leg support assembly and coupled inertial loading system is used to load the hamstrings. The loading system has an overall 10:1 gear ratio, such that a set of disks rotates 10 times faster than the leg itself. This allows the limited knee range of motion in the MR magnet to generate sufficient accelerations to load the lengthening hamstrings. We compared hamstring muscle activities and knee joint moments when using the inertial loading with that observed using an elastic loading system. Our results indicate the target muscle is activated while lengthening under the inertial load, but not under the elastic load. Repeatability measurements show that a periodic and accurate motion can be achieved to ±1° for both maximum flexion and extension. In addition, we also confirmed that our device works in a standard MR magnet, and is compatible with an extremity wrap coil and plethysmograph trigger device. The next test will be to acquire dynamic images in an MR magnet.

Introduction:

Current imaging techniques used in musculoskeletal radiology are primarily static, and hence do not provide a direct assessment of how the system behaves under functional conditions that involve dynamic movement and loading. The next generation of imaging tools would allow one to visualize tissue and joint behavior during movement. Such information could lend new insights into musculoskeletal biomechanics, and provide an improved basis for diagnosing impairments and assessing clinical outcomes.

Dynamic musculoskeletal imaging requires a device that can guide movement and load musculoskeletal structures within the constraints of imaging hardware and software. Previous devices found in literature often consisted of a weight/pulley system which applied a constant force to a subject's limb. For example, a device developed by Asakawa *et al*. had subjects lie supine while the limb was guided through flexion/extension motion [1].

Patel *et al*. also designed a weight bearing apparatus to measure knee kinematics (Figure 1). Their device consisted of a weight/pulley system in which the subject pressed a foot plate to apply a constant load of 133 N [2].

Figure 1: Weight bearing apparatus to measure knee contact area.

Pappas *et al*. had their subjects perform elbow flexion/extension using two calibrated elastic cords (Figure 2). They measured the muscle tissue motion of the biceps brachii in the upper arm using Cine PC imaging [3].

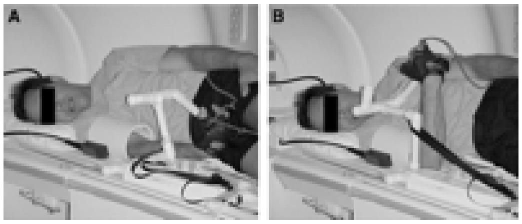

Figure 2: Elastic load device for measuring biceps velocity.

We have developed a magnetic resonance (MR) compatible device to dynamically load the hamstrings during a lengthening contraction, which is the type of condition that can induce musculotendon injury during high-speed running. The device will be used in conjunction with phase contrast imaging, which acquires images over many cycles of repeated motion to determine tissue velocity at every pixel within the imaging plane. Our device will induce repeatable, lengthening, low-load contractions of the hamstring muscles. The device is non-ferrous, fits within the bore of a standard MRI machine and allows for a flexible MR coil to be placed around the fixed thigh. A trigger is used to signal the start and end of each cycle of motion.

We designed a device that will use an inertial load to emulate the type of loading seen by the hamstring during sprinting. Our rationale for using an inertial load instead of an elastic or constant load is as follows: In the running gait cycle, the hip flexes and the knee rapidly extends during mid-swing, seen in Figure 3.

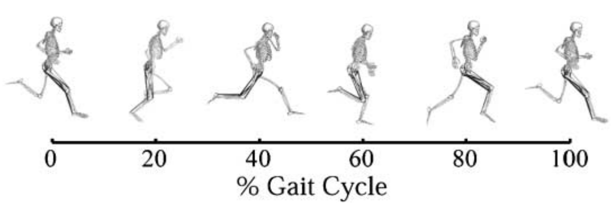

Figure 3: The running gait cycle. We are focusing on the 2nd half of swing phase, approximately 70-100% of the gait cycle [4].

Deceleration of the limb occurs during late swing prior to foot contact. The deceleration of the shank induces an inertial torque about the knee. The hamstrings are active and lengthening during late swing to counteract the inertial loading. Active, lengthening muscle contractions under large load are the type of conditions that can induce muscle injury [5]. We want to mimic the type of loading associated with injury in an MR magnet, so we are using an inertial load to simulate running.

The purpose of our paper is to validate that our device works to load the hamstring in a physiologic setting and also ensures repeatability of the motion due to constraints of dynamic imaging.

Methods:

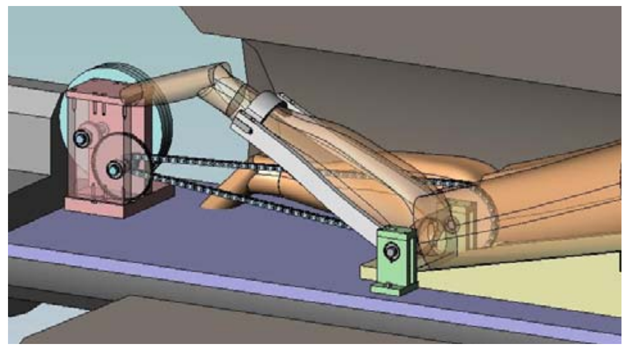

Figure 4: The device as modeled in an MRI bore.

The device consists of an inclined mat upon which the subject lies in a prone position to flex the hips (Figure 4). The imaged leg was strapped to a leg support system consisting of two shaped polyethylene bars connected to a Delrin® shaft located inside ball bearing structures on either side of the knee (Figure 5).

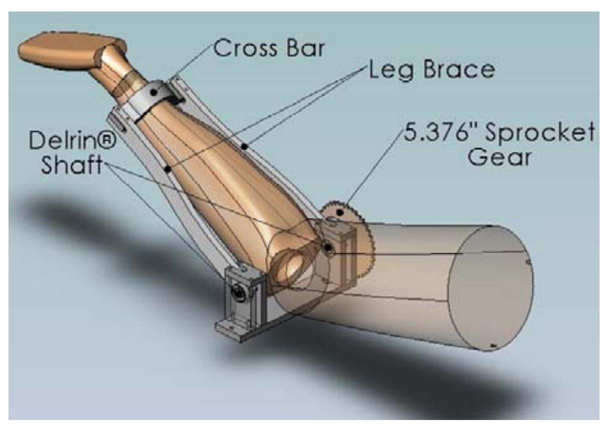

Figure 5: The leg support assembly.

Inside the knee attached to one Delrin® shaft is a 45-tooth sprocket that turns at the same angular velocity as the shank. This sprocket is attached to a plastic chain that connects to another 12-tooth located at the feet. When combined with the large sprocket at the knee, the gear ratio is increased by 3.75 to allow for added torque to be placed on the knee. The one inch sprocket is attached an auxiliary Delrin® shaft inside of a gear box. Spur gears are used to further increase the overall gearing ratio. A large 80-tooth spur gear on the auxiliary shaft meshes with a 30-tooth spur gear. The small spur gear was attached to a cantilever Delrin® shaft which supports the inertial disks (Figure 6). The manner in which the sprockets and spur gears mesh allows an overall gearing ratio of 10:1. The inertia disks are fashioned out of solid surface material and provide different amounts of inertia that rotate at a larger angular velocity than the shank due to the gear ratio of the sprockets. This system provides an inertial force on the hamstring during eccentric, or lengthening, contraction.

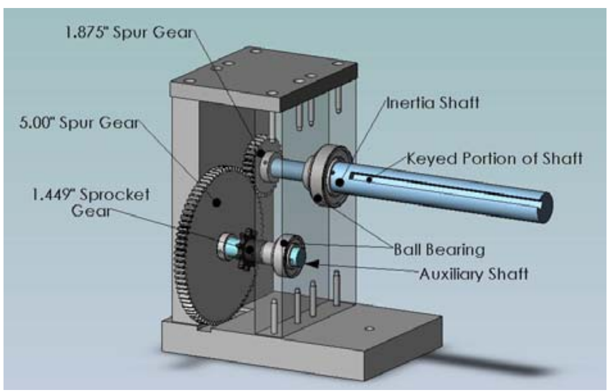

Figure 6: The gear box if the inertia loading system.

As a first step in validating this device, we tested its motion in a motion analysis lab where we measured muscle activity of the hamstring. As seen in running, the hamstrings are active at 90% of the running gait cycle when the leg is in extension.

The first test we performed was to set up the device in the motion analysis lab to assess the motion of the limb and muscle activity throughout that motion. The device was placed in the center of the room surrounded by seven infrared cameras mounted on the walls. Two reflective markers were placed on the device, one at the pivot point by the knee, and another at the distal end of the leg brace. The infrared cameras captured the motion of the markers, and computed the knee angle. For this test, a metronome was used to help the subject move his or her shank at the desired frequency.

EMG leads were also placed on the long head of the biceps femoris and on the medial hamstrings to collect electrical activity of the hamstring during motion. Two types of loading were used in this experiment: a spring load that was seen on other previous prototypes and our designed inertial load [3]. The subject was asked to perform 24 cycles per minute for 5 minutes for each loading condition.

Results

The data was analyzed by plotting the knee angle to show how repeatable and periodic a subject can perform the flexion/extension movement (Figure 7). Maximum flexion angle and maximum extension angles all ranged between ±1° from the averaged maximum angle.

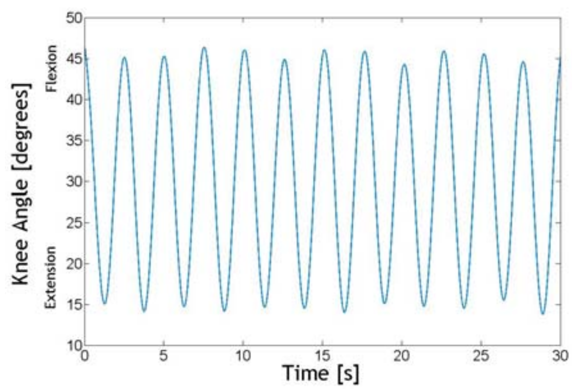

Figure 7: The repeatability of the knee angle over 12 cycles: Average range of motion was 45.5°±1.04 (max) and 14.6°±0.85 (min).

Figures 8 and 9 compare two different loading configurations our device can place on the hamstrings. Figure 8 superimposes the EMG activity on top of the knee angle for an inertially loaded hamstring, whereas the Figure 9 depicts the hamstring EMG data and knee angle under a spring/elastic load. For an inertial load, when the subject's leg extends going from full flexion (maximum point) to full extension (minimum point) the hamstring is active.

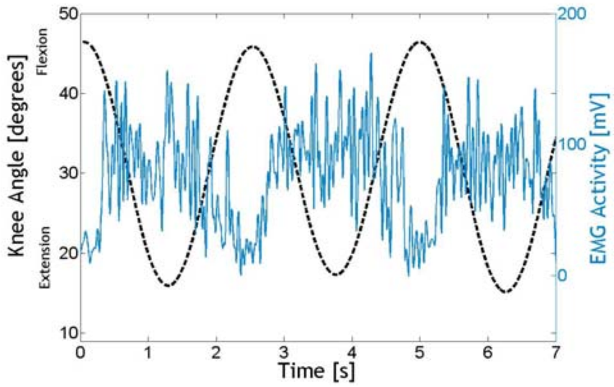

Figure 8: This graph shows the EMG data of hamstring activation superimposed with the cycle of motion during inertial loading. The hamstrings become most active when the knee is fully extended.

In contrast, when using the spring loaded device, the activity of the hamstring is diminishing at this same point (extension). Because the hamstrings are not active at the point of interest, it is shown that a spring/elastic load does not create a physiological force on the hamstrings.

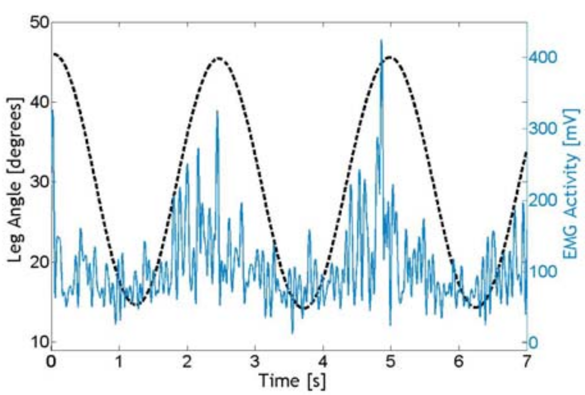

Figure 9: This graph shows the EMG data of hamstring activation superimposed with the cycle of motion during elastic loading. The hamstrings become most active when the knee is undergoing flexion.

Discussion:

Hamstring muscle strains are one of the most frequent injuries in sports that involve sprinting. Many of these injuries involve the biceps femoris, the largest of the three muscles that comprise the hamstrings. It is thought that injury occurs in late swing phase of the running gait cycle (Figure 3).

When a hamstring injury occurs, muscle fibers tear apart and ultimately form scar tissue in the process of healing. This scar tissue affects muscle performance and may increase the risk of re-injury. Our ultimate goal was to use dynamic imaging to determine the effects of the scar tissue on muscle velocity.

Our results show that we can achieve a repeatable, harmonic motion with our device, which is necessary for the dynamic imaging application. We are also able to physiologically load the hamstrings in a way that mimics conditions that make the muscle susceptible to strain injury. We have proven that our device is MR compatible in that it does not contain any ferrous materials and that it fits within the constraints of the MR bore size. Additionally, the device accommodates an extremity wrap MR coil for the thigh and is compatible with a plethysmograph triggering device placed near the ankle.

Our device has some inherent flaws that need to be take care of before further testing can occur. One point of weakness is the shaft holding the large sprocket at the knee. Because of the large torque applied by the inertia disk assembly, backlash occurs at low angular velocities and there is a possibility for shearing to occur. We will be addressing this problem by replacing the shaft with brass or bronze. Furthermore, the chain tends to go slack at high inertial loads, which creates discontinuities in the acceleration of the inertial disks. Tensioners or idlers will be added to resolve this problem.

The next stage in validating our prototype is to obtain the CINE-PC pulse sequence and begin dynamic imaging using subjects who have previously injured their hamstrings. In-vivo experiments will be performed in a 1.5T whole-body MRI scanner. The device and subject will be placed into the MRI and the subject will perform the same 24 cycles per minute as stated previously. The subject will use a metronome to help time the frequency of the motion as was done in the motion capture experiments. Dynamic images will be collected of the hamstrings during this motion for inertial loads and the muscle velocity measured. Regions of interest will be assigned to various positions along the muscle fibers and tracked throughout the cycle of motion. Velocity can be determined by integrating the position with respect to time of each region of interest between two different images [3].

We need *in vivo* measurements of muscle velocity to not only treat/rehabilitate hamstring injuries, but also to validate biomechanical modeling assumptions and develop a better understanding of muscle function. Most models of musculotendon contraction use simple representations, which may not accurately reflect what happens *in vivo* [3]. Since muscles are more complex than this, researchers need devices like ours to control the load placed on a muscle so an accurate representation of muscle velocity can be measured.

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