BIOMECHANICAL ANALYSIS OF FORWARD LUNGE EXERCISES WITH VARIOUS EXTERNAL LOADINGS

Student ID: 1175060
ENGG*3150 F24
School of Engineering, University of Guelph, Guelph, Canada

INTRODUCTION

This lab report investigates the biomechanics of forward lunges (FL) with dumbbells as external loadings, and its relationship with lower limb muscle activation and joint angles. This information is valuable in rehabilitation science, where exercises such as FL and weights play a crucial role in training muscle control and strength [1]. The hypothesis is that a FL with dumbbell weights on each hand will bring an increased muscle activation, corresponding to increased muscle control, and ultimately allows for an optimal FL that can be used for rehabilitation purposes, reflecting the increased neuromuscular demand as an external load is added compared to a normal lunge. Previous studies have shown that an optimal rehab-focused exercise will require symmetrical loading and strength development, as well as lateral stabilization and control, which is what this research will delve into [2]. Lateral stabilization is the ability of muscles to control side-to-side movements and maintain balance in the frontal plane, preventing issues like pelvis tilting or knee collapsing inward. This property will be analyzed using the data from the electromyography (EMG) sensors to determine of the FL encourages high muscle activation, which corresponds to high muscle control. Symmetrical loading and strength development require an even distribution of forces across both sides of the body, promoting balanced muscle activation, proper posture, and a reduced risk of imbalances or overuse injuries [2]. This property will be tested through the use of joint angle data and analyzing the direction in both the frontal plant and sagittal plant to determine whether a forward lunge with dumbbells allows for even balance. The expected results for this report is that while the FL with dumbbells will allow higher muscle activation and therefore greater control due to the external loading compared to a normal FL, the dumbbells might create an uneven weight distribution across the body, contributing to an off-centered center of mass, which could ultimately result in poor posture with the hips tilting forward and the knee collapsing inward.

METHODS

A 20-year-old, 182.3 cm and 85.4 kg participant gives written informed consent and approval from the Research Board of Ethics for this study. The participant wore tight-fitting athletic shorts, shirts, and shoes. The experiment involved performing a forward lunge (FL) at a comfortable step length while holding 25 lb dumbbells in each hand and returning to the original standing position. The dumbbells were positioned hanging at the sides of the body, with the palms facing inward (medially). In addition, a control trial is conducted with the participant performing a normal FL without any external loadings, which will be vital to compare data. Each FL variation is recorded for 3 trials.

To start setting up the tools for data collection during the trials, the VICON Data Acquisition (DAQ) and Nexus Software (v2.16, Vicon Motion Capture Systems Ltd., Oxford, UK), is turned on and calibrated, and the sEMG Sensors (Trigno, Delsys Inc., Natick, MA, USA) were paired to the VICON Nexus software. The EMG sensors are quickly taken out of their case and swiped with a magnet to activate the sensor. Prior to attaching the EMG sensors, the skin is prepped by lightly rubbing sandpaper at the site of the attachment, which will further reduce noise. The EMG sensors were placed on the skin, with the arrow on the sensor facing upwards, on the following locations adhering to SENIAM guidelines: the muscle belly of the vastus lateralis, biceps femoris, and rectus femoris. These will be the muscles of interest for this experiment. In addition, the VICON Motion Capture System (Vicon Motion Capture Systems Ltd., Oxford, UK) is used to track the participant's movement. The space where the trials will be recorded is calibrated with a wand, and masked to ensure any reflective objects are ignored during the recording of the trials. Reflective markers are attached to the right leg and pelvis with double-sided tape, following the standard guidelines provided by HAS-Motion. The pelvis markers followed the CODA Pelvis model with the names RICT, LICT, RFT, LIPS, and RIPS. The thigh markers followed

Thigh Model 1 with RFT, LFT, RTH1, RTH2, RTH3, RTH4, RFLE, and RFME. Shank Model 1 was used with markers named RFME, RFLE, RSK1, RSK2, RSK3, RSK4, RFAL, and RTAM. Ensure that the markers are visible and are not covered by clothing throughout the FL trials.

Using the raw data, the VICON Nexus software was used to gap-fill any missing markers that were not picked up by the cameras. A static trial where the participant ensures all markers are visible throughout the recording is vital for this step. Visual3D (Professional 2025, HAS-Motion, Kingston, ON, Canada) was used to further process and compute a skeleton model, analyze and export joint angle data on the knee and hips. During this step, the data underwent a low-pass Butterworth filter with zero-lag, 6 Hz cutoff frequency to remove noise. MATLAB (R2024b, The MathWorks Inc., MA, USA) is used to analyze the processed and exported data. To process the joint angles data, graphs were generated to visualize the joint angles throughout the forward lunge trials. Specific points of interest, such as the peak joint angles and range of motion (ROM), were identified using the ginput() function in MATLAB, allowing for manual selection directly on the plots. The sagittal plane (forward/backward motion) was the primary focus for the analysis, with the X-values representing the ROM in the sagittal plane, and the Y-values representing the ROM in the frontal plane. This approach provided clear insights into the relationship between joint angles, and the external loading conditions during the forward lunge. To process the EMG data, a 2nd order Butterworth bandpass filter was applied with cutoff frequencies set at 20 Hz and 400 Hz. The filter was implemented using the filtfilt() function, which ensured zero-phase distortion and prevented lag in the filtered data. After filtering, the EMG signals were rectified by taking their absolute values to simplify the analysis. An envelope detection process followed, which required applying a second Butterworth low-pass filter. This filter was also implemented using the filtfilt() function, maintaining zero-phase distortion while smoothing the rectified and normalized EMG signals. This step ensured clear representation of the muscle activation data.

RESULTS

The joint angles data show the comparison of the joint angles in both the X and Y direction, where X is the movement in the sagittal plane, and Y is the movement in the frontal plane (Figure 1).

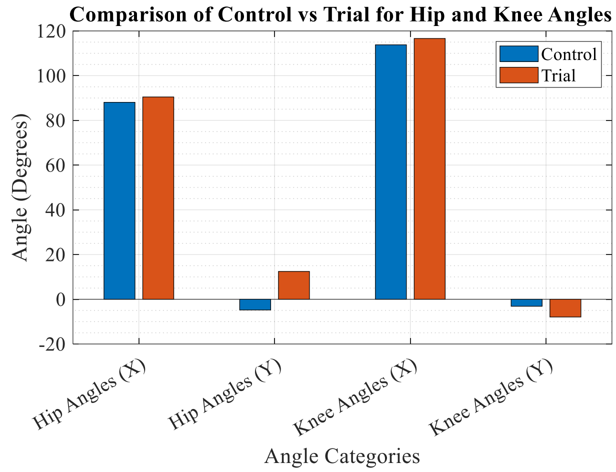

Figure 1: Joint angles data for control and dumbbell trial.

The vastus lateralis appears to primarily control the FL in both the control and trial condition (Figure 2).

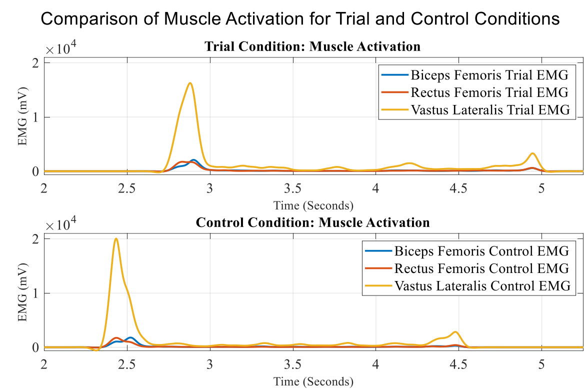

Figure 2: All muscle groups EMG data of trial and control FL conditions.

For the vastus lateralis EMG data, the control is higher in magnitude than the trial condition (Figure 3).

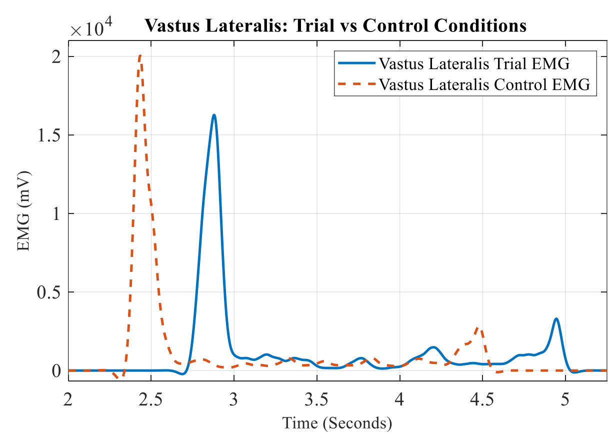

Figure 3: Vastus lateralis EMG data of trial and control FL conditions.

The biceps femoris have similar muscle activation in both conditions, with higher activation towards the end of the FL (Figure 4).

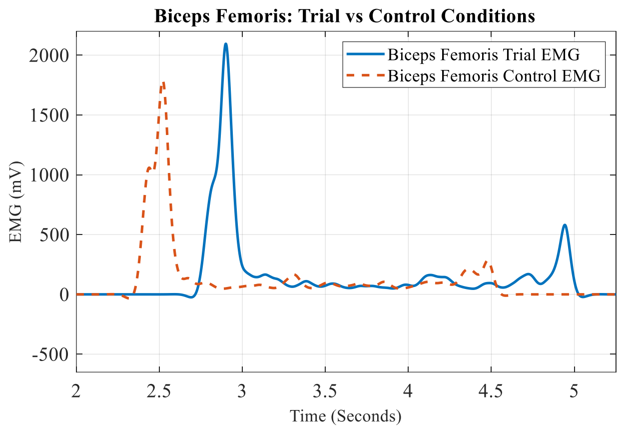

Figure 4: Biceps femoris EMG data of trial and control FL conditions.

The biceps femoris shows similar results as the biceps femoris, which shows that both muscles may play similar roles in the FL (Figure 5).

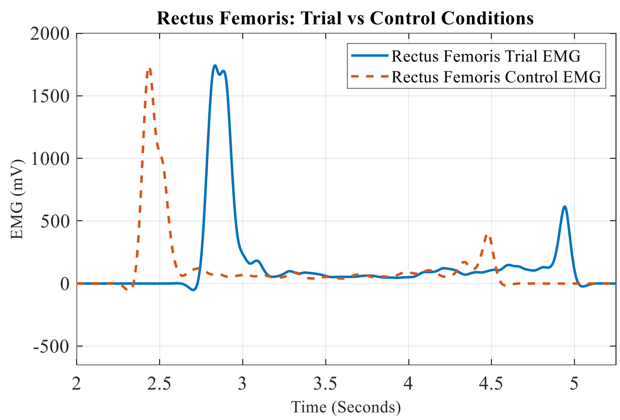

Figure 5: Rectus femoris EMG data of trial and control FL conditions.

DISCUSSIONS

The relationship between an externally loaded forward lunge (FL), EMG magnitude, and joint angles was not as expected, emphasizing the impact of dumbbell weights on muscle activation. Analysis of the EMG data shows that the vastus lateralis is the primary muscle controlling the FL (Figure 2). A significant increase in muscle activation magnitude is observed when comparing the trial condition to the control condition. According to a previous study, the vastus lateralis plays a key role in stabilizing the knee during forward lunges, particularly in unstable conditions where it maintains symmetrical balance and prevents the knee from collapsing [3]. The introduction of dumbbell weights creates an instability factor, increasing muscle activity to compensate for the weight shift. However, this result may not fully demonstrate this relationship, potentially due to muscle fatigue from multiple trials performed beforehand.

The biceps femoris, or hamstring, does not play a dominant role in controlling the forward lunge, which was unexpected as it is a major lower-limb muscle group [1]. The results indicate that the biceps femoris is most activated during the initial stages of the forward lunge (Figure 4). This can be attributed to its role as an antagonist muscle that stabilizes and resists excessive motion during knee flexion, rather than generating significant force or control [4]. Greater activation may occur with dynamic external loads, such as swinging weights or resisting additional forces. Similarly, the rectus femoris shows activation magnitudes comparable to the biceps femoris in both the control and trial conditions (Figure 5). Both muscles are primarily activated at the start of the forward lunge, serving as antagonist muscles [4]. Increased activation is observed at the end of the lunge as the participant returns to the starting position and the knee extends.

The data and results of the joint angles in the sagittal (X-values) and frontal (Y-values) planes highlight the relationship between joint mechanics, lateral stabilization, and symmetrical load distribution during forward lunges. The hip angles along the sagittal plane show minimal differences between the control and trial conditions, indicating that the range of motion (ROM) in the forward lunge was well-maintained despite the applied external loads, and the hips do not tilt forward as a result. This contrasts with the expected outcome, where the off-centered weight of the dumbbells might have led to poor posture. Instead, this suggests that a forward lunge with external loading can effectively contribute to symmetrical load development, where the hip and knee flexors play a role in maintaining balance in the sagittal plane and minimizing the risk of imbalances that could otherwise lead to injury. However, the knee angles in the X-direction increased slightly in the trial condition (+6°), suggesting an increased ROM as a compensation mechanism for the external load.

For the angles in the frontal plane, or the Y-values, the hip angles show a notable difference between the control (-4.79 °) and trial condition (12.44 °). This is a result of lateral instability, which is due to the external load shifting the center of mass forward and challenging the stability in the frontal plane, where the pelvis is tilting in the lateral direction. A previously conducted study shows that hip muscle strength and stability play a critical role in controlling frontal plane movements, with weaknesses and fatigue in stabilizing muscles contributing to increased pelvic tilt, especially under externally loaded conditions which may explain the pelvic tilt in the results [5]. Furthermore, the knee angles in the Y-direction indicate greater abduction in the trial condition (-7.93°) compared to the control (-3.13°), with the negative values representing the abduction movement. These results emphasize the critical role stabilizing muscles play during forward lunges, as weak or fatigued muscles can contribute to increased pelvic tilt.

The results of the study done on the FL and external loadings provide insights on whether the FL with dumbbells as external loading is an optimal F

In future research and trials, analyzing shoulder muscles such as the ___ would be insightful to see how upper-limb muscles deal with external loadings and stabilizing weights during dynamic exercises [6]. Working with a participant with a history of lower-limb injuries, or rehab patients may also provide n impactful result on the practical applications of exercise and their role in improving lateral stabilization and muscle control through repeated trials over a long period of time.

CONCLUSIONS

A key finding is that different muscle groups are primarily in control than others and have different key roles for the same dynamic exercise.

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Table 1: Joint moments and EMG magnitudes at various weights for isometric trial 1.

Mass (lbs)	Joint moment (Nm)	Biceps Brachii EMG Magnitude (mV)	Brachioradialis EMG Magnitude (mV)
4	5.70	0.075	0.018
7	10.0	0.085	0.045
10	14.2	0.133	0.100
15	21.4	0.213	0.093