EFFECTS OF FATIGUE ON LIMB COORDINATION WITHIN THE FRAMEWORK OF THE UNCONTROLLED MANIFOLD ANALYSIS

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Introduction: Motor redundancy is a fundamental characteristic of human movement that facilitates compensatory adjustment [1] particularly to internal factors such as fatigue. Previous investigations on motor control of bouncing gaits, running, and hopping, during fatigue have revealed that humans strategically manipulate the variability of joint-level kinematics (joint segment angles) to minimize variations in performance-level variables, notably the center of mass trajectory [2]-[4]. These findings suggest that the central nervous system (CNS) exploits motor redundancy as a compensatory strategy, enabling the maintenance of task performance even under conditions of heightened fatigue.

Existing literature has explored motor control during fatigue in the context of dynamic activities like running and hopping. However, an analysis of how lower limb joint coordination changes to stabilize leg dynamics following fatigue is notably absent. This study aims to pursue two objectives: 1) investigate how humans employ interjoint coordination to stabilize leg length throughout squat cycles, and 2) examine the impact of fatigue on the synergy structure responsible for stabilizing leg length during repetitive squatting. We posited two hypotheses: 1) subjects will coordinate segment angles to stabilize leg length throughout the entire squat cycle, with a specific emphasis on the target squat depth, and 2) the stabilization of leg length would remain unaffected despite increasing fatigue levels.

Methods: 8 healthy participants (5F/3M) gave informed consent prior to participating in this Georgia Tech IRB approved protocol.

Experimental Data Collection: Participants underwent an exercise protocol designed to induce targeted fatigue in major leg extensor muscle groups. They performed repetitive squats to a target knee flexion angle of 90° at a 50-bpm pace. The protocol continued with blocks of continuous exercise until either the participant squatted for 4 consecutive minutes or failed 3 successive squat cycles to the target on beat. Following this, 3 maximal single-leg jumps (SLJs) were attempted. If the target height was achieved in any of these jumps, the fatigue protocol was repeated until all three SLJs failed to reach the target height, or 5 4-minute blocks of squats were accomplished.

Locomotor EMG Analysis: The first and last 30 seconds of the 1st and 5th block band-pass EMG signals of major muscles [5] were transformed to measure the mean power frequency (MPF) as an indicator of fatigue [6].

UCM Kinematic Model: A 4 segment kinematic MATLAB model was created to determine whether joint segments coordinate to stabilize leg length within key phases of a squat cycle [7]. A Jacobian relating segment angles to leg length was derived using segment angles averaged over the first block's first 30 squats. IMA (Index of Motor abundance) values were calculated for the 1st and 5th block of squats. The changes in MPF and IMA within each block were averaged across subjects. MPF was compared using a 1-tailed, paired t-tests with an alpha level of 0.05.

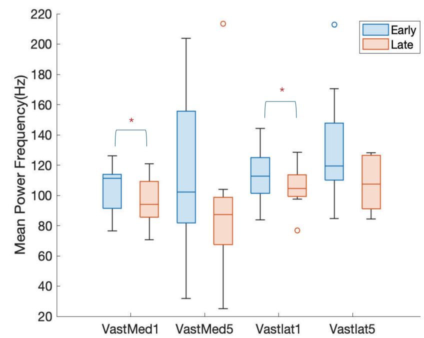

Figure 1: MPF (n=8) for Vastus Lateralis and Vastus medialis in early and late stages of Block 1 and 5. (* = $p<0.05$)

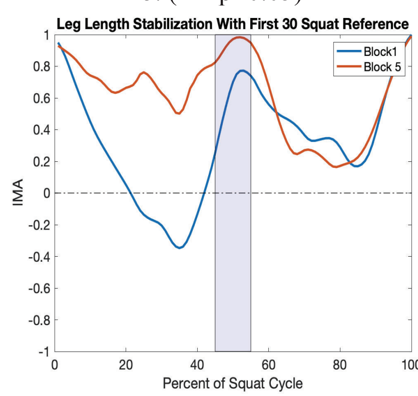

Figure 2: IMA of leg length control. Data represents mean IMA values across subjects (n=3). The shaded region represents target squat depth.

Results & Discussion: There was a general trend of lower MPF for major muscle groups with exercise indicating fatigue (Fig. 1). MPF significantly declined within Block 1 for both muscles. A preliminary UCM analysis shows that leg length is generally stabilized throughout the entire squat cycle for both Block 1 and 5. IMA reached a peak at the target squat depth (45-55% of squat cycle) in Block5 (Fig. 2). As MPF decreased, IMA increased within the descent phase (0-45% of squat cycle) and at the target depth (45-55% of squat cycle). The increase of IMA with fatigue suggests that the subjects increasingly selected a consistent joint coordination strategy favoring the stabilization of leg length.

Significance: These preliminary results provide additional insights on how the human locomotor system can maintain limb-level performance through a compensation strategy that exploits joint-level motor abundance in the presence of fatigue.

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References: [1] Preatoni et al. (2013) *Sports Biomech* 12(2); [2] Muide et al. (2016), *Hum Mov Sci* 48; [3] Möhler et al. (2019), *Hum Mov Sci* 66:133-141; [4] Möhler et al. (2022), *Biology (Basel)11(6);[5]* Signorile et al. (1994), *J Strength Cond Res* 8(3):178-183. [6] Chaffin. (1973), *J Occup Med.*(4):346-54; [7] Auyang et al. (2009), *Exp Brain Res.*192(2):253-64