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Neuromechanical synergies in single-leg landing reveal changes in movement control

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ABSTRACT

Our purpose was to examine changes in single-leg landing biomechanics and movement control following alterations in mechanical task demands via external load and landing height. We examined lower-extremity kinematic, kinetic, and electromyographic (EMG) adjustments, as well as changes in movement control from neuromechanical synergies using separate principal component analyses (PCA). Nineteen healthy volunteers (15M, 4F, age: 24.3 ± 4.9 y, mass: 78.5 ± 14.7 kg, height: 1.73 ± 0.08 m) were analyzed among 9 single-leg drop landing trials in each of 6 experimental conditions (3 load and 2 landing height) computed as percentages of subject bodyweight (BW, BW + 12.5%, BW + 25%) and height (H12.5% & H25%). Condition order was counterbalanced, including: 1.) BW·H12.5, 2.) BW + 12.5·H12.5, 3.) BW + 25·H12.5, 4.) BW·H25, 5.) BW + 12.5·H25, 6.) BW + 25·H25. Lower-extremity sagittal joint angles and moments (hip, knee, & ankle), vertical ground reaction force (GRFz), and electrical muscle activity (gluteus maximus, biceps femoris, vastus medialis, medial gastrocnemius, & tibialis anterior muscles), were analyzed in each trial. Biomechanical adjustments and neuromechanical synergies were assessed using PCA. Subjects reduced effective landing height through segmental configuration adjustments at ground contact, extending at the hip and ankle joints with greater load and landing height ($p \leqslant 0.028$ and $p \leqslant 0.013$, respectively), while using greater medial gastrocnemius preactivation with greater load ($p \leqslant 0.006$). Dimension reduction was observed under greater mechanical task demands, compressing and restructuring synergies among patterns of muscle activation, applied loads, and segmental configurations. These results provide insight into movement control and potential injury mechanisms in landing activities.

1. Introduction

Landing from a jump or an elevated surface is a common movement and mechanism of injury in sport and performance settings (James, Dufek, & Bates, 2000; Yeow, Lee, & Goh, 2009, 2011; Zhang, Bates, & Dufek, 2000). Although extensively investigated in bilateral conditions (Devita & Skelly, 1992; Dufek & Bates, 1990, 1992; James, Dufek, & Bates, 2006) single-leg landing has a greater incidence of injury (Ali, Robertson, & Rouhi, 2014), which deserves attention in the context of movement control. Drop landing provides a gross motor task with a high degree of experimental control, while performance repetitions expose distinct neuro-musculoskeletal solutions among individuals. Motor solutions are thought to arise from individual, environmental, and task constraints that shape movement outcomes (Newell, 1986), which

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characterize movement strategies (Bates, 1996; James & Bates, 1997; James, Bates, & Dufek, 2003; James, Atkins, Dufek, & Bates, 2014). During movement execution, the available biomechanical degrees of freedom (DOF) exceed those required to successfully perform a task (Bernstein, 1967; Davids, Glazier, Araujo, & Bartlett, 2003). Movement coordination is therefore simplified through dimension reduction (Latash, 2010; Lohse, Jones, Healy, & Sherwood, 2013; Turvey, 1990).

Neuromuscular input allows DOF 'freezing' through segmental coupling, providing a reduced subset of control units described using functional DOF (James & Bates, 1997; Li, 2006) and synergies, though the number of mechanical DOF does not change (Chvatal & Ting, 2012; Diedrichsen, Shadmehr, & Ivry, 2009; Todorov, 2006; Turvey, 1990). Mathematically, synergies are defined by systematic correlations among effectors (muscles, joints, or limbs), which characterize coordinated movement (Diedrichsen et al., 2009; Latash, 2010). Conceptually, the mechanical and muscle linkages, as well as the underlying neural organization describe a synergy (Diedrichsen et al., 2009; Latash, 2010; Turvey, 1990). Synergistic control of human movement has been experimentally identified in balance, gait, and landing, describing not only the correlation structure among movement outcomes (Diedrichsen et al., 2009), but also the neural activation patterns controlling movement (Chvatal & Ting, 2012; Kipp et al., 2014). Mechanical and neuromuscular adjustments following mechanical task demand manipulations, including load and landing height, provide mechanisms for load accommodation, moderating external forces (Caster & Bates, 1995; James et al., 2003), and potentially altering movement control through neuromuscular input. Lesser gross motor variability, expressed through fewer neuromechanical synergies, may therefore provide fewer available motor solutions under greater mechanical task demands, leading to repetitive tissue loading and possible overuse injury, as the rate of mechanical breakdown exceeds the rate of physiological repair (James, 2004; James et al., 2000).

Principal component analysis (PCA) has gained increasingly widespread application in biomechanical investigations, reducing relevant information from multi-dimensional signals into independent sources of variation (Brandon et al., 2013; Daffertshofer, Lamoth, Meijer, & Beek, 2004; Federolf, Boyer, & Andriacchi, 2013; Kipp & Palmieri-Smith, 2012; Richter, O'Connor, Marshall, & Moran, 2014). Given the outlined descriptions of movement coordination and synergies, PCA can provide interpretations in line with concepts from motor control (Latash, 2010; Li, 2006; Lohse et al., 2013; Scholz & Schoner, 1999), providing a multivariate time series measure of movement variability. Collectively, PCA has been applied to datasets from kinematic, kinetic, and EMG sources, demonstrating utility among a number of tasks (Daffertshofer et al., 2004; Kipp, Redden, Sabick, & Harris, 2012; Kipp et al., 2014; Li, 2006; Richter et al., 2014). Applications of PCA to biomechanical time series data allow the entire movement phase to be analyzed, extending beyond discrete point analyses (Richter et al., 2014), thus adding to the understanding of movement control.

Our purpose was to examine changes in single-leg landing biomechanics and movement control following alterations in mechanical task demands via external load and landing height. We examined lower-extremity kinematic, kinetic, and electromyographic adjustments, as well as changes in movement control from neuromechanical synergies using separate principal component analyses. We tested two hypotheses. Under greater mechanical task demands, (1) subjects would demonstrate neuromuscular accommodation (increasing muscle activation and joint flexion angles, with greater GRFz and joint extensor moments) in response to greater external load and landing height, while providing (2) fewer available movement solutions, expressed through fewer neuromechanical synergies. The ability to detect a reduction in the number of synergies may provide a means of predicting and preventing injuries.

2. Methods

2.1. Subjects

We recruited 19 physically active, healthy volunteers from the general population representing a convenience sample (15M, 4F, age: 24.3 ± 4.9 y, mass: 78.5 ± 14.7 kg, height: 1.73 ± 0.08 m). Each subject provided informed consent prior to participation, as required by the Institutional Review Board at the affiliated institution.

2.2. Instrumentation

Each subject was fitted with standardized footwear (Adidas® Response Competition). Subjects were encouraged to bring their own tight fitting clothing (i.e. spandex shorts/shirt), but were offered laboratory clothing if unavailable. We used small backpacks for adding load with standard iron weight plates and manipulated landing height with an adjustable platform.

We collected lower-extremity kinematic, kinetic, and EMG data using a 10-camera motion capture system (16-point spatial model; Vicon Plugin-Gait; MX-T40S; 200 Hz), synchronized force platform (Kistler Type 9281CA; 2000 Hz), and 16-channel EMG system (Noraxon Myosystem 2000; 2000 Hz). EMG signals were recorded using dual surface (Ag/AgCl) differentially amplified (gain: 1000, bandwidth: 16–1000 Hz at −3 dB, common mode rejection ratio: 135 dB), and passive electrodes (inter-electrode spacing: 2.0 cm, Noraxon # 272).

2.3. Procedure

Subjects completed a standardized warm-up, including approximately 5-min of treadmill running and 1–2 single-leg landings prior to collected trials. Each subject identified a preferred support limb for completing single-leg landings from