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Full Length Article

Modulation of lower extremity joint stiffness, work and power at different walking and running speeds

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ABSTRACT

Locomotion task and speed changes affect dynamic joint function. Walking and running require different coordination patterns of lower extremity joint mechanics. These coordination differences can result in measurable changes in kinematic and kinetic patterns. When locomotion speed changes, the functional role and movement strategy of each joint is altered. A deeper understanding of joint level mechanics and functional interactions will benefit rehabilitation programs and assistive device development. In this study, joint stiffness, joint mechanical work and power were assessed, as they relate to dynamic function of joints during locomotion. Ten young healthy subjects (5 males, 5 females) participated in a treadmill walking (0.8–2.0 m/s) and running (1.8–3.8 m/s) study. When running speed increased, the stiffness of all three joints tended to increase. The ankle joint played a dominant role during the stance phase of running, generating more positive work than the knee ($p = .003$) and hip ($p = .0001$). The knee and hip joint were more dominant in walking and running swing phase energy absorption and generation, respectively. When locomotion speeds increased, stance phase ankle positive work, swing phase knee negative work, and hip joint positive work tended to increase. These findings suggest that change of locomotion speed or task results in definitive changes to lower extremity joint level mechanics patterns.

1. Introduction

Locomotion is an important function in human activities, and walking and running are the primary forms. Both activities require complex coordination between different muscles, tendons and ligaments (Ferris, Louie, & Farley, 1998; Kuo, 2007), associated with kinematic and kinetic pattern changes of joints and segments (Li, Van Den Bogert, Caldwell, Van Emmerik, & Hamill, 1999). Walking can be loosely described as 'vaulting' over relatively stiff legs (Geyer, Seyfarth, & Blickhan, 2006), while running is often described as a bouncing movement, on 'springy' legs (Geyer et al., 2006; McGowan, Grabowski, McDermott, Herr, & Kram, 2012). To better investigate and interpret the dynamics of walking and running, a simplified inverted pendulum model (Adamczyk & Kuo, 2009; Kuo, 2007; McGrath, Howard, & Baker, 2015) and spring mass model (Alexander, 1992; Farley, Glasheen, & McMahon, 1993; Farley & Gonzalez, 1996; McGowan et al., 2012; McMahon & Cheng, 1990) have both been used in previous research. In human locomotion, the lower extremity can be regarded as a system requiring joint level dynamic pattern coordination. When locomotion speeds change, lower extremity joints serve different functional roles (Qiao & Jindrich, 2016). Faster locomotion speeds coincide with an increase in kinetic energy of the whole body, due to more joint level mechanical work and power being generated than is absorbed (Schache,

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Brown, & Pandy, 2015). When walking at continuously increasing speeds, a spontaneous walk to run transition occurs at a fairly predictable speed (around 2.17 m/s) (Segers, Aerts, Lenoir, De Clercq, & De Clerq, 2007). Gait transition speed is influenced by how speed changes are introduced and there appears to be a redistribution of joint level mechanical work among the lower extremity joints (Farris & Sawicki, 2012). Change of locomotion speed may require different strategies, within one locomotion state and between different locomotion states (e.g., gait transition). A more detailed investigation is needed to better understand how joint level functional roles and mechanical patterns are coordinated among the different phases of locomotion, in response to changes in speed. A deeper understanding of joint level mechanics and functional interactions will benefit rehabilitation programs and assistive device development.

Joint level mechanics during locomotion requires the elastic potential characteristics of the musculotendinous system to absorb energy during the braking phase of early stance and generate energy during the propulsive phase in late stance (Cavagna, 1977; Kuitunen, Komi, Kyröläinen, & Kyrolainen, 2002). The stretching and shortening phenomenon under loading conditions in different joints during locomotion has been described as having spring-like behavior (Kuitunen et al., 2002). Intersegmental displacement as a function of joint moment has been defined as dynamic joint stiffness (Crenna & Frigo, 2011; Davis & DeLuca, 1996; Gabriel et al., 2008). Previous studies have compared lower extremity joint stiffness in walking and running. The ankle joint moment-angle relationship has been investigated between males and females, as well as across different age ranges (Crenna & Frigo, 2011; Gabriel et al., 2008). It was reported that male subjects tended to have a higher ankle joint stiffness and higher joint work in normal walking, and ankle joint stiffness was not significantly different between different ages (Crenna & Frigo, 2011; Gabriel et al., 2008). Frigo, Crenna, and Jensen (1996) investigated the effect of different walking speeds on ankle, knee and hip joint angle-moment relationships. They reported that the various calculated slopes during different phases of plotted angle-moment relationships of each joint indicate speed dependence. However, findings of joint stiffness in running condition have been mixed. Ankle joint stiffness has been reported to remain unchanged when running from 2.5 to 6.5 m/s, as well as from 70% to 100% maximum running speed (Arampatzis, Bruk, & Metzler, 1999; Kuitunen et al., 2002). However, it has also been reported that ankle joint stiffness was higher in sprinting compared to slower speed running (Stefanyshyn & Nigg, 1998). However, knee joint stiffness has been reported to increase with increased running speed (Arampatzis et al., 1999; Kuitunen et al., 2002). Knee joint stiffness tended to be higher than ankle joint stiffness and the knee joint was observed to have a higher magnitude of extension compared to the ankle joint in running (Günther & Blickhan, 2002). It remains that little is known about the concurrent stiffness patterns of lower extremity joints across locomotion speeds and between locomotion states. This study provides further information regarding joint stiffness patterns while walking and running at various speeds.

Modulation of joint level mechanical work and power is known to contribute to dynamic movement in different locomotion speeds (Anahid Ebrahimi, Goldberg, & Stanhope, 2017). Farris and Sawicki (2012) found that the relative contribution of the ankle, knee and hip to total positive power did not change across walking and running speeds. In other findings, lower extremity joint work and average power did not proportionally increase from walking to sprinting (Schache et al., 2015). Instead, the contribution to the total average power tended to transfer between joints as speed changed (Schache et al., 2015). However, Anahid Ebrahimi et al. (2017) reported that stance phase relative ankle joint positive and negative work increased with walking speeds. With these apparent contradictions, the relationship between stance phase joint level mechanical loading and response, and the specific functional roles played by the joints in energy generation and absorption between stance phase and swing phase in different locomotion speeds remains unclear. More detailed comparisons are needed about the transfer mechanisms used during stance and swing phase joint work and average power in both walking and running.

Joint stiffness and joint level energy exchange mechanics are regarded as two major aspects of dynamic joint function (Crenna & Frigo, 2011). Previous studies have investigated joint stiffness, joint work and power patterns separately in different activities, with occasionally contradictory findings. However, more information is needed about the combination of joint stiffness, work and power in both walking and running, to more fully understand the relationship between stance phase joint dynamic loading response (specifically, in braking and propulsion phases), joint mechanical work and average power generation and absorption, when locomotion tasks and speeds change. This study provides a separate analysis of stance and swing phase joint work and average power, providing a more detailed view of lower extremity joint function in different phases of walking and running across different speeds. An increased understanding of these relationships should provide a better framework for future assistive device development, which may be suitable for multiple tasks of human locomotion and better emulate the functional behavior of human limbs (Shamaei, Sawicki, & Dollar, 2013). The purpose of this study was to investigate lower extremity joint level stiffness, stance and swing phase joint work and average power in walking and running across a range of speeds. We hypothesized that: (1) lower extremity joints stiffness would increase when locomotion speeds increased, and (2) joint stiffness, joint work and power would be higher in running compared with walking.

2. Methods

Ten abled-bodied subjects participated in the study (23 ± 5.3 years, 170 ± 11.2 cm, 67 ± 14.2 kg). All subjects signed informed written consent approved by the university's institutional review board before participation. Subjects were excluded based on any of the following criteria: a history of neurologic deficits or other musculoskeletal disorders that would affect gait, a history of rheumatic diseases, or a history of unexpected falls in the previous six months.

After measuring height and body mass of each subjects, 55 *retro*-reflective markers were placed on the skin surface, adapted from a previously published whole body marker set (Sawers & Hahn, 2012). Subjects were first instructed to walk on a force-instrumented treadmill (Bertec, Inc., Columbus, OH) at seven increasing speeds, from 0.8 to 2.0 m/s (at 0.2 m/s intervals), for 90 s per stage. Then