Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

The contribution of counter-rotation movements during fall recovery: A validation study

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ARTICLE INFO

Article history:
Accepted 14 July 2018
Available online xxxx

Keywords:
Balance reactions
Momentum
Postural disturbances
Upper extremities
Stability

ABSTRACT

Three mechanisms of maintaining standing stability include M_1 – moving the COP within the base of support, M_2 – segment counter-rotation, and M_3 – applying an external force. To date, the contributions of these mechanisms have not been quantified for the response to an external postural disturbance. The purpose of this study was to evaluate the construct validity of measures that quantify the M_2 contribution to anteroposterior fall recovery. We evaluated the whole-body rotation contribution, as well as a measure specific to arm motion (M_{ARMS}). With segment counter-rotation as the main focus of this study, we examined standing feet-in-place responses to treadmill-induced falls. The treatment validity of our measures was assessed by comparing unconstrained responses to those with constrained arm motion. The convergent validity of our measures was assessed by correlating peak shoulder flexion and extension velocities with counter-rotation contributions. Eleven unimpaired participants responded to anteroposterior belt accelerations from a treadmill, and the M_2 and M_{ARMS} contributions were quantified from three-dimensional segment motion. The treatment validity of these measures was partially supported. Constraining the arms reduced M_2 for anterior, but not posterior falls. Conversely, M_{ARMS} was reduced for posterior, but not anterior falls. Convergent validity was supported for M_{ARMS} ($r = 0.64$–0.78), but not M_2 ($r = -0.40$ to -0.15). These results support the use of M_{ARMS} over M_2 when interested in the role of arm motion. Given that arm constraints did not change the contribution of M_{ARMS} during a forward fall, unimpaired participants may not necessarily rely on arm motion as part of their recovery strategy in this context.

1. Introduction

Falls are the leading cause of accidental, nonfatal injury in the United States (9.3 million in 2015) (Centers for Disease Control and Prevention, 2018). Many falls are due to external causes, such as a push, pull, trip, or slip. For example, 44–75% of all falls in older adults (Morfitt, 1983; Yasumura et al., 1996) and 34% of falls in individuals with chronic stroke (Schmid et al., 2013) are due to extrinsic causes. In laboratory studies, older adults (Crenshaw and Grabiner, 2014; McIlroy et al., 1999) and individuals with chronic stroke (Geurts et al., 2005) have demonstrated an impaired ability to recover from external postural disturbances. By identifying the biomechanical mechanisms by which individuals recover from such disturbances, we can determine the specific effects of neuromuscular impairment on fall recovery, as well as the relevant benefits of interventions to improve fall-recovery skill.

Standing balance is maintained via three quantifiable mechanisms: moving the center of pressure (COP) within the base of support (M_1), counter-rotating segments about the whole-body COM (M_2), and applying an external force (M_3) (Hof, 2007). An example of the first mechanism is the "ankle strategy" of generating an ankle moment to maintain anteroposterior stability (Runge et al., 1999). When the "ankle strategy" is not sufficient for maintaining standing stability, a step can extend the base of support. To supplement the first strategy, or to help prevent a recovery step, the second strategy of segment counter-rotation can be employed. An example of this mechanism is the "hip strategy" of joint flexion in response to an anterior disturbance (Runge et al., 1999) or the rapid rotation of the upper extremities. The third mechanism of applying an external force is exemplified when an individual uses

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https://doi.org/10.1016/j.jbiomech.2018.07.025
0021-9290/

a handrail or safety harness. In the absence of an external force (M_3), the relative contributions of M_1 and M_2 during volitional movements are influenced by the presence and magnitude of trunk and arm motion, the size of the base of support, and the plane of interest (Åberg et al., 2011; Hof, 2007; Ko et al., 2015). To our knowledge, the contributions of these mechanisms have not been evaluated for the response to an external postural disturbance.

Many studies have focused on the role of "ankle strategies", "hip strategies", and step kinematics during fall recovery (Pavol et al., 2001; Runge et al., 1999; Troy et al., 2008). An aspect often ignored is how reactive arm motion contributes to stabilization. Rapid arm movements during stepping responses benefit whole-body rotation and the COM trajectory during the recovery response (Cheng et al., 2014; Marigold, 2002; Pijnappels et al., 2010; Roos et al., 2008; Tang and Woollacott, 1998; Troy et al., 2009). With age, arm reactions are delayed, and the arm motion can transition from compensatory patterns to protective patterns that alter the fall impact location (Allum et al., 2002; Merrill et al., 2017; Roos et al., 2008). Constraining arm motion limits the ability to recover from an anterior fall with a feet-in-place strategy, and a faster stabilization from the fall is associated with greater arm momentum (Cheng et al., 2015). Although arm motion plays a role in fall recovery, the specific contribution of such motion, which is dependent on the motion timing, arm momentum, and contributions of other mechanisms, has not been quantified. The contribution of the counter-rotation mechanism (M_2), as proposed by Hof (2007), is a promising means to doing so. However, this measure has not been validated in the context of recovering from an external postural disturbance, and an *arm-specific* measure of counter-rotation contribution has not been proposed.

The purpose of this study was to evaluate the construct validity of measures that quantify the counter-rotation contribution to recovery from anterior and posterior external postural disturbances. We evaluated a measure that included whole-body counter-rotation (Halvorsen, 2010; Hof, 2007) as well as a modified measure that focused solely on upper extremity rotation. With segment counter-rotation as the main focus of this study, we examined standing feet-in-place responses with no recovery steps. In order to support the treatment validity of our measures, we hypothesized that both the whole-body and arm-specific counter-rotation contributions would be reduced for fall-recovery responses in which arm motion was constrained. In order to support the convergent validity of our measures, we hypothesized that both the whole-body and arm-specific counter-rotation contributions would be positively correlated with peak shoulder flexion and extension velocities when the arms were not constrained.

2. Methods

2.1. Data collection

Eleven adults with no self-reported neuromuscular impairment or injury (mean (standard deviation), age = 22.2 ± (2.3) years, BMI = 22.6 (3.1) kg/m^2) were recruited for this study. This study was approved by the University of Delaware institutional review board, and all participants provided informed consent prior to participation.

Participants stood on a computer-controlled treadmill (ActiveStep®, Simbex, Lebanon, NH, Fig. 1) and were instructed to "try to prevent a step" in response to rapid, 400 ms belt translations (Crenshaw and Kaufman, 2014). Initial belt accelerations began at 0.5 m/s^2, lasting a period of 200 ms followed by a 200 ms deceleration phase, in total resulting in a 1 cm total displacement. For subsequent trials, the initial accelerations were

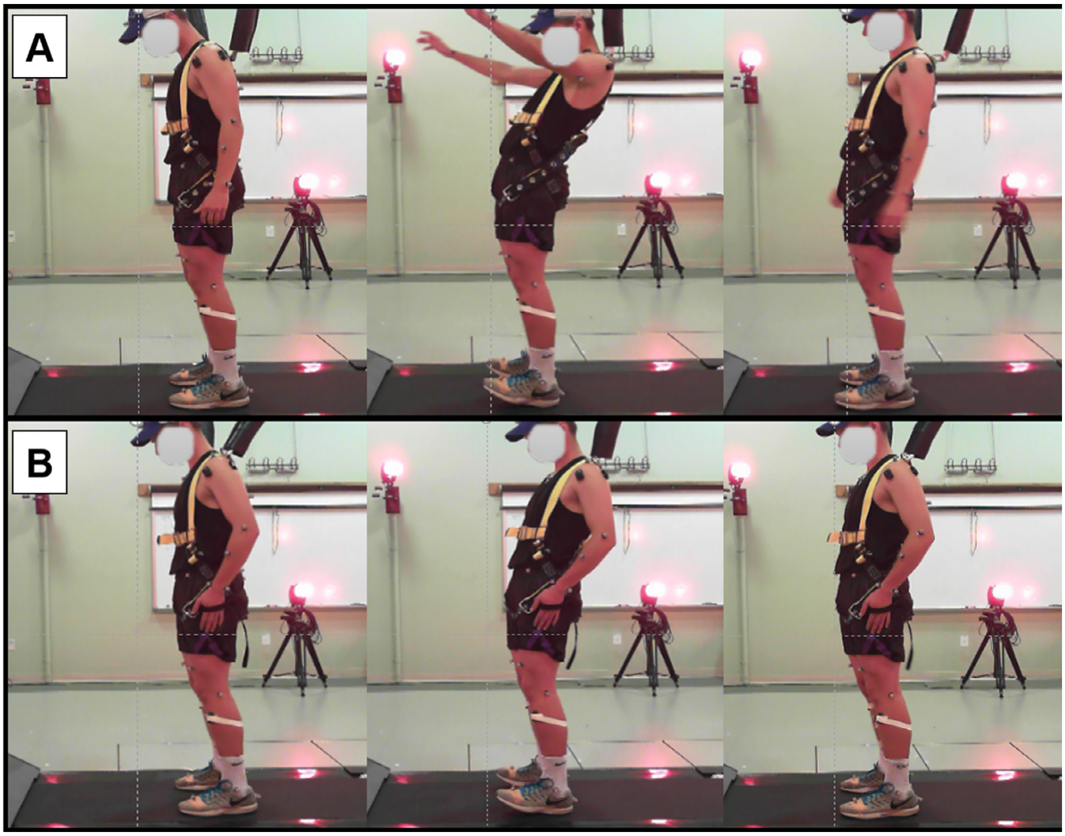

Fig. 1. A participant successfully recovers from a posterior postural disturbance (initial acceleration = 3.5 m/s^2) in unconstrained (A) and arms-constrained (B) conditions.

Please cite this article in press as: Rapp van Roden, E.A., et al. The contribution of counter-rotation movements during fall recovery: A validation study. J. Biomech. (2018), https://doi.org/10.1016/j.jbiomech.2018.07.025