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Whole-body and Segmental Contributions to Dynamic Balance in Stair Ambulation are Sensitive to Early-Stage Parkinson's Disease*

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***Abstract*—Stair ambulation is commonplace in daily living activities, yet biomechanically more challenging compared to level-ground walking. With reduced lower-limb muscle strength and increased rigidity of extremities, people with Parkinson's disease (PD) experience impaired balance and higher incidence of falls each year. However, the regulation of whole-body dynamic balance of individuals with PD in stair walking is unclear. Whole-body angular momentum (*H*) is a useful metric for assessing dynamic balance that accounts for the angular movements of all body segments about the body center-of-mass (COM). In this study we investigated the regulation of *H* and segmental contributions to *H* during stair ascent and descent walking in individuals with PD compared to healthy subjects. During stair descent, the magnitude of sagittal-plane *H* increased in participants with PD compared to healthy subjects in ipsilateral (most affected side) leg stance. Meanwhile, the legs contributed more to sagittal-plane *H* in individuals with PD compared to healthy subjects. During stair descent walking, the magnitude of transverse-plane *H* was also greater in participants with PD compared to healthy subjects during the second half of ipsilateral leg gait cycle. The increased magnitude of negative (i.e., forward) sagittal-plane *H* in the ipsilateral stance of stair descent walking suggests that individuals with PD experience greater difficulties maintaining their forward rotation during such tasks.**

***Clinical Relevance*—This study highlights the need for dynamic balance of individuals with PD during stair descent walking and the potential of whole-body and segmental *H* in assessing dynamic balance of this population.**

I. Introduction

Commonplace in daily living activities, stair walking is biomechanically more challenging compared to level-ground walking as it requires increased joint moments [1] to raise/lower body COM, slow down ambulation speed [2], and maintain safe foot placements. This may lead to increased need for dynamic balance during stair ambulation in muscle-strength-deficient or balance-impaired populations such as the elderly. Stair walking has been thought as one of the most difficult daily tasks for the older populations [3] and stair falls are a leading cause of accidental death of the elderly [4]. Previous studies have also shown greater challenges during stair walking in individuals with neurological disorders such as stroke [5] and diabetic peripheral neuropathy [6]. The enhanced demand of dynamic balance of stair walking increases the risk of falling in daily lives. Understanding dynamic balance regulation of the impaired populations during stair locomotion is important for their ultimate independence of daily living.

People with Parkinson's disease (PD) have impaired balance with about 60% of them falling each year [7]. Reduced lower limb muscle strength has been associated with falls in this population [7], which could lead to increased challenge in biomechanically demanding tasks of stair walking. Researchers have shown that individuals with PD exhibit worse trunk balance or reduced rhythmicity of trunk movements during stair ambulation relative to level walking, with poorer trunk movements during stair descent compared to stair ascent [8]. Similarly, greater trunk roll angle was observed in stair walking of people with PD compared to the healthy [9]. Furthermore, rigidity and tremor of extremities are one of the principal symptoms of PD, which could further increase the dynamic balance need of this population during stair walking. Previous studies have shown that individuals with PD exhibit decreased inter-limb coordination between upper and lower extremities during level walking compared to healthy people, which was related to clinically poorer gait and posture [10]. With impaired inter-limb coordination, people with PD also need to compensate for their balance control asymmetries by increasing exerted force of the leg of the clinically least affected side [11]. Collectively, individuals with PD face greater challenges and may develop specific strategies in maintaining whole-body dynamic balance during stair walking relative to normal people, which need to be thoroughly comprehended for their rehabilitation and quality of life.

Whole-body angular momentum (***H***) is a quantitative measure for assessing dynamic balance that accounts for the angular movements of all body segments about the body COM. ***H*** is useful in human locomotion analysis because it is directly related to whole-body kinetics. The time rate of change of ***H*** equals the net external moment about the body COM, which is the cross product of ground reaction forces and external moment arms (distance between center of pressure and body COM). Furthermore, ***H*** is regulated by individuals through muscle force generation [12], and thus, is related to not only join kinematics but also joint kinetics.

H is suitable for assessing dynamic balance as it is tightly regulated by healthy individuals during normal walking [13]. Frontal-plane ***H*** has been shown to be negatively correlated with clinical test scores of Dynamic Gait Index and Berg Balance Scale in post-stroke normal walking with larger ***H*** indicating worse balance [14]. ***H*** has also been used to assess

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dynamic balance in stair ambulation of healthy and impaired populations. The range of frontal-plane $\boldsymbol{H}$ of the healthy was greater in stair ascent walking compared to level walking, while the range of transverse and sagittal plane $\boldsymbol{H}$ decreased in stair walking [15]. Our previous study also showed increased frontal-plane $\boldsymbol{H}$ and trunk contributions to frontal-plane $\boldsymbol{H}$ of healthy individuals during cut-stairs walking compared to level-ground normal walking [16], [17]. In individuals with a unilateral transtibial amputation, the range of sagittal-plane $\boldsymbol{H}$ was larger relative to able-bodied individuals during stair descent [18]. However, how $\boldsymbol{H}$ is regulated by individuals with PD during stair walking is still unclear.

Therefore, the purpose of this study was to investigate the regulation of whole-body dynamic balance, measured by $\boldsymbol{H}$, during stair ascent and descent walking in individuals with PD compared to healthy subjects. Segmental contributions to $\boldsymbol{H}$ were also analysed to understand the interlimb coordination strategy used by subjects with PD to maintain dynamic balance. We hypothesized that the magnitude of sagittal-plane $\boldsymbol{H}$ would be larger during stair walking in individuals with PD compared to healthy persons. We expected this because larger range of sagittal-plane $\boldsymbol{H}$ was found during stair walking of individuals with amputation [18]. We also hypothesized that lower limbs are the primary contributors to the increased sagittal-plane $\boldsymbol{H}$ because they are relatively large in moment of inertia and move more quickly during walking relative to the torso.

II. Methods

A. Subjects and protocol

Five individuals with early stage PD (Table 1) and five healthy subjects (4 male, 1 female; 25.2±2.5 years; 1.75±0.11 m; 66.8±12.2 kg) participated in this study. All participants provided their written informed consent to participate in the experiment protocol that was approved by the Institutional Review Board. All participants with PD in this experiment were determined as Hoehn and Yahr stage 1 or 2 by a licensed and practicing Physical Therapist, indicating unilateral or bilateral motor impairment without balance difficulties. Participants with PD reported their disease duration, falls experienced, most affected side and weekly exercise length as in Table 1. All subjects with PD were using their prescribed dosage of medication at the time of testing, and none of them have a deep brain stimulator implanted. In the experiment, participants walked up and down an instrumented four-step stair case (15 cm riser, 30 cm tread) with handrails as well as over a level-ground walkway (Fig. 1). Participants were instructed to use handrails if they felt unsafe. Trials in which they used the handrails were excluded in the analyses.

B. Data collection and processing

A 10-camera motion capture system (Vicon) working at 100 Hz was used to capture 66 markers to track whole-body motion. Recorded experiment data were processed in Visual3D (C-Motion). A low-pass fourth-order Butterworth filter with a cut-off frequency of 6 Hz was used for the kinematic data. A 12-segment model (Fig. 1) was built for each subject to calculate body kinematics. $\boldsymbol{H}$ and segmental contributions to $\boldsymbol{H}$ were calculated as

$$\vec{H} = \sum_{i=1}^{n} \left[I_i \vec{\omega}_i + \left(\vec{r}_i - \vec{r}_{body} \right) \times m_i \left(\vec{v}_i - \vec{v}_{body} \right) \right].$$

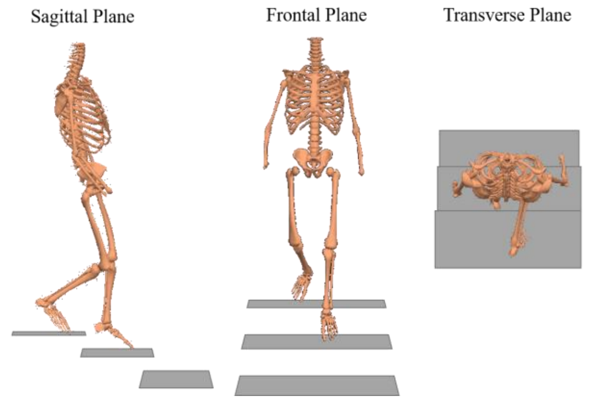

Figure 1. Twelve-segment human body model used to calculate whole-body angular momentum ($\boldsymbol{H}$) in three anatomical planes.

where I_i and $\vec{\omega}_i$ are the moment inertia and angular velocity of segment i, respectively; $\vec{r}_i$ and $\vec{r}_{body}$ are the position vectors of segment i and body COM , respectively; $\vec{v}_i$ and $\vec{v}_{body}$ are the linear velocity vectors of segment i and body COM, respectively; $n = 12$ for the computations of $\boldsymbol{H}$. Upper-limb contribution to $\boldsymbol{H}$ ($n = 4$) includes angular momentum of left and right forearms and upper arms, and lower-limb contribution to $\boldsymbol{H}$ ($n = 6$) includes angular momentum of left and right thighs, shanks and feet. Trunk contribution to $\boldsymbol{H}$ ($n = 2$) includes angular momentum of torso and pelvis. $\boldsymbol{H}$ and segmental contributions to $\boldsymbol{H}$ were normalized by body mass and height, and in ipsilateral (most affected side of subjects with PD) or left leg gait cycle. We defined the positive sagittal-plane $\boldsymbol{H}$ as rotation toward backward, positive frontal-plane $\boldsymbol{H}$ as rotation away from the left or ipsilateral leg, and positive transverse-plane $\boldsymbol{H}$ as rotation toward the left or ipsilateral leg.

TABLE I. Characteristics of Subjects with PD

	Subject				
	1	2	3	4	5
Demographics					
Age	57	62	66	67	62
Gender	M	F	F	M	F
Height (m)	1.72	1.72	1.72	1.8	1.72
Mass (kg)	94.8	54.4	82.6	92.5	63.5
Health conditions					
Years since PD diagnosis	8	5	1.5	3	6
Falls experienced	1	0	0	0	0
Most affected side	R	R	R	L	L
Hoehn and Yahr stage	2	1	1	2	2
Weekly Exercise (min)	840	240	80	600	480

C. Statistical analysis

The trajectories of $\boldsymbol{H}$ and segmental contributions to $\boldsymbol{H}$ were compared between individuals with PD and healthy subjects during three tasks of stair ascent, stair descent and level walking. Statistical parametric mapping (SPM) t-test was used for comparisons (α=0.05) [19].

III. Results

A. Whole-body angular momentum

We analyzed the trajectories of $\boldsymbol{H}$ in three anatomical planes (Fig. 2). There were no differences of $\boldsymbol{H}$ between

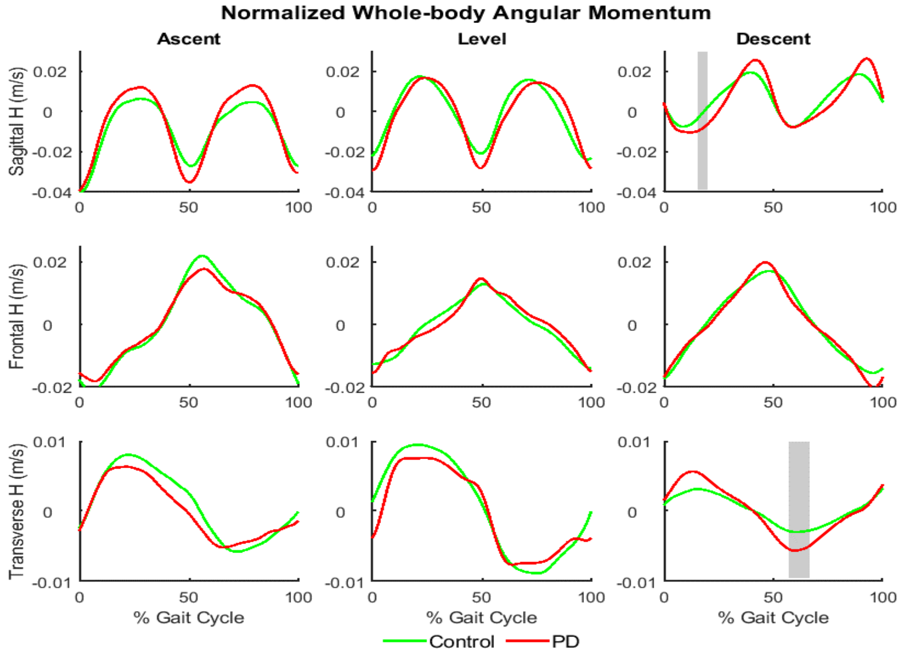

Figure 2. Three-dimensional normalized whole-body angular momentum (***H***) of healthy subjects (green) and individuals with PD (red) during stair ascent, level-ground and stair descent walking. Grey vertically shaded areas indicate regions of statistical significance from a SPM t-test (α=0.05).

individuals with PD and healthy subjects during stair ascent and level walking. During stair descent walking, the magnitude of sagittal-plane ***H*** increased over 90% in participants with PD compared to healthy subjects in 15-20% gait cycle. The magnitude of transverse-plane ***H*** also increased over 60% in participants with PD in 57-67% gait cycle.

B. Segmental contributions to H

We calculated segmental contributions to ***H*** to study the interlimb coordination in dynamic balance regulation of people with PD. There was no difference of segmental contributions to ***H*** between individuals with PD and healthy subjects during stair ascent and level walking. During stair descent walking, the magnitude of lower-limb contribution to sagittal-plane ***H*** increased over 88% in participants with PD compared to healthy subjects in 15-21% gait cycle (Fig. 3).

In stair descent walking, lower limbs, trunk and upper limbs, respectively, contribute on average 96%, 6% and -2% of sagittal-plane ***H*** in PD patients during 15-21% gait cycle. Meanwhile, lower limbs, trunk and upper limbs, respectively, contribute on average 84%, 12% and 2% of sagittal-plane ***H*** in healthy subjects. In individuals with PD, lower limbs, trunk and upper limbs, respectively, contribute 105%, 4% and -8% of transverse-plane ***H*** during 57-67% gait cycle. In healthy

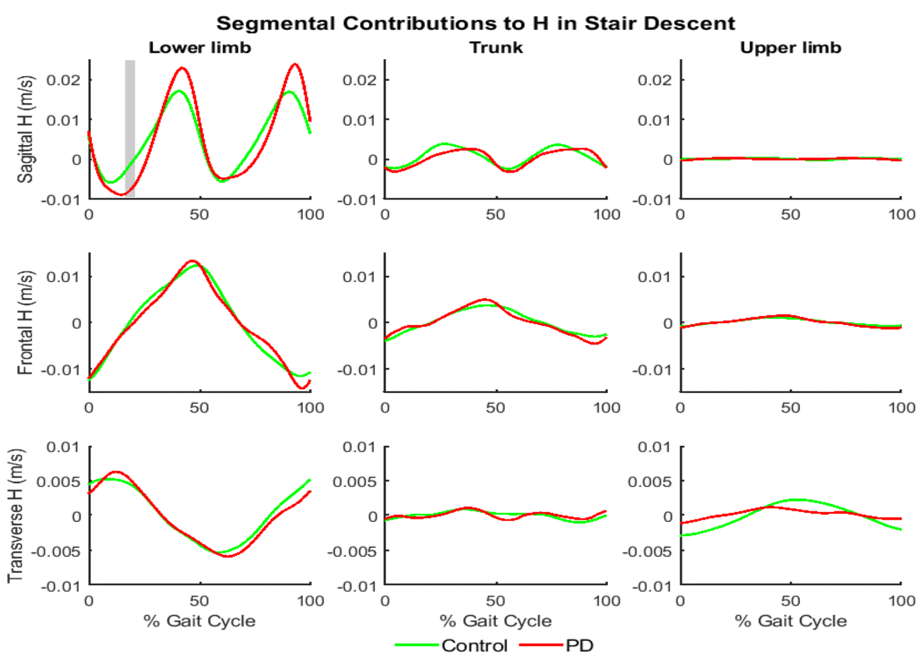

Figure 3. Segmental contributions to three-dimensional normalized whole-body angular momentum (***H***) of healthy subjects (green) and individuals with PD (red) during stair descent walking. Grey vertically shaded areas indicate regions of statistical significance from a SPM t-test (α=0.05).

subjects, lower limbs, trunk and upper limbs, respectively, contribute 178%, -7% and -69% of transverse-plane $\boldsymbol{H}$ during 57-67% gait cycle.

IV. Discussion

In this study, we used $\boldsymbol{H}$ to investigate the regulation of dynamic balance in individuals with PD relative to healthy persons during stair walking. Our first hypothesis that the magnitude of sagittal-plane $\boldsymbol{H}$ would be larger during stair walking in individuals with PD was supported. The increased magnitude of negative sagittal-plane $\boldsymbol{H}$ in the ipsilateral stance of stair descent walking suggests that individuals with PD experience greater difficulties maintaining forward dynamic balance in such tasks. Since tighter regulation of sagittal-plane $\boldsymbol{H}$ is favourable for fall prevention during stair descent walking [15], individuals with PD may experience higher risk of falling during this task.

Our second hypothesis that lower limbs are the primary contributors to the increased $\boldsymbol{H}$ was also supported. During the ipsilateral stance of stair descent walking, lower-limb contributions to sagittal-plane $\boldsymbol{H}$ was greater in persons with PD compared to the healthy (Fig. 3). This may be due to the impaired function of the lower limb, especially the rigidity of the ipsilateral leg. Since sagittal-plane angular momentum of lower limbs are in opposite direction during gait [20], decreased movements of ipsilateral leg would lead to greater lower-limb contributions to sagittal-plane $\boldsymbol{H}$. Furthermore, the magnitude of transverse-plane $\boldsymbol{H}$ was greater in individuals with PD in the contralateral leg stance of stair descent walking. This may be due to the rigidity of upper limbs of persons with PD, as the upper limb angular momentum was larger in the healthy to compensate the lower-limb angular momentum.

Conventional clinical assessments, for example, the Dynamic Gait Index have been used to assess dynamic balance of individuals with PD. However, these clinical tests either measure the time used or rate qualitative scores for performing the tasks, and cannot provide quantitative measure of the whole trajectory of movement. Researchers have also used the trunk harmonic ratio to assess dynamic balance of individuals with PD [8], which may overlook the contributions of extremities in maintaining dynamic balance. Recently, $\boldsymbol{H}$ has been used to assess walking dynamic balance of individuals with neuromotor conditions, such as hemiparesis and post-stroke [14], [21] [22]. The results of this study may suggest the potential of $\boldsymbol{H}$ to assess dynamic balance of PD populations, although it may be limited by the moderate number of subjects and the relatively young age of control subjects. While this study was conducted in a gait lab with motion capture system, sparse wearable sensors and machine learning algorithms may be used to assess dynamic balance based on $\boldsymbol{H}$ in real-time [23]. Future research should investigate the relationship between $\boldsymbol{H}$ and clinical balance test scores of people with PD.

References

[1] T. P. Andriacchi, G. B. Andersson, R. W. Fermier, D. Stern, and J. O. Galante, “A study of lower-limb mechanics during stair-climbing.,” *J. Bone Joint Surg. Am.*, vol. 62, no. 5, pp. 749–57, Jul. 1980.

[2] A. Stacoff, C. Diezi, G. Luder, E. Stüssi, and I. A. Kramers-De Quervain, “Ground reaction forces on stairs: Effects of stair inclination and age,” *Gait Posture*, vol. 21, no. 1, pp. 24–38, 2005.

[3] J. D. Williamson and L. P. Fried, “Characterization of older adults who attribute functional decrements to ‘old age,’” *J. Am. Geriatr. Soc.*, vol. 44, no. 12, pp. 1429–1434, 1996.

[4] J. K. Startzell, D. A. Owens, L. M. Mulfinger, and P. R. Cavanagh, “Stair negotiation in older people: A review,” *J. Am. Geriatr. Soc.*, vol. 48, no. 5, pp. 567–580, 2000.

[5] A. C. Novak and B. Brouwer, “Kinematic and kinetic evaluation of the stance phase of stair ambulation in persons with stroke and healthy adults: A pilot study,” *J. Appl. Biomech.*, vol. 29, no. 4, pp. 443–452, 2013.

[6] S. J. Brown, J. C. Handsaker, F. L. Bowling, A. J. M. Boulton, and N. D. Reeves, “Diabetic peripheral neuropathy compromises balance during daily activities,” *Diabetes Care*, vol. 38, no. 6, pp. 1116–1122, 2015.

[7] S. S. Paul, C. Sherrington, C. G. Canning, V. S. C. Fung, J. C. T. Close, and S. R. Lord, “The relative contribution of physical and cognitive fall risk factors in people with Parkinson’s disease: A large prospective cohort study,” *Neurorehabil. Neural Repair*, vol. 28, no. 3, pp. 282–290, 2014.

[8] Z. J. Conway, T. Blackmore, P. A. Silburn, and M. H. Cole, “Dynamic balance control during stair negotiation for older adults and people with Parkinson disease,” *Hum. Mov. Sci.*, vol. 59, no. December 2017, pp. 30–36, 2018.

[9] A. L. Adkin, B. R. Bloem, and J. H. J. Allum, “Trunk sway measurements during stance and gait tasks in Parkinson’s disease,” *Gait Posture*, vol. 22, no. 3, pp. 240–249, 2005.

[10] R. T. Roemmich, A. M. Field, J. M. Elrod, E. L. Stegemöller, M. S. Okun, and C. J. Hass, “Interlimb coordination is impaired during walking in persons with Parkinson’s disease,” *Clin. Biomech.*, vol. 28, no. 1, pp. 93–97, 2013.

[11] T. A. Boonstra, A. C. Schouten, J. P. P. Van Vugt, B. R. Bloem, and H. Van Der Kooij, “Parkinson’s disease patients compensate for balance control asymmetry,” *J. Neurophysiol.*, vol. 112, no. 12, pp. 3227–3239, 2014.

[12] R. R. Neptune, C. P. McGowan, and A. L. Hall, “Muscle Contributions to Frontal and Transverse Plane Whole-Body Angular Momentum During Walking,” *Proc. Int. Soc. Biomech. 2011 Conf.*, vol. 129, 2011.

[13] H. Herr and M. Popovic, “Angular momentum in human walking.,” *J. Exp. Biol.*, vol. 211, no. Pt 4, pp. 467–481, 2008.

[14] C. R. Nott, R. R. Neptune, and S. A. Kautz, “Relationships between frontal-plane angular momentum and clinical balance measures during post-stroke hemiparetic walking.,” *Gait Posture*, vol. 39, no. 1, pp. 129–34, Jan. 2014.

[15] A. K. Silverman, R. R. Neptune, E. H. Sinitski, and J. M. Wilken, “Whole-body angular momentum during stair ascent and descent,” *Gait Posture*, vol. 39, no. 4, pp. 1109–1114, 2014.

[16] W. Li, N. T. Pickle, and N. P. Fey, “Time evolution of frontal plane dynamic balance during locomotor transitions of altered anticipation and complexity,” *J. Neuroeng. Rehabil.*, vol. 17, no. 1, pp. 1–12, 2020.

[17] W. Li and N. P. Fey, “Neuromechanical Control Strategies of Frontal-Plane Angular Momentum of Human Upper Body During Locomotor Transitions,” in *2018 7th IEEE International Conference on Biomedical Robotics and Biomechatronics (Biorob)*, 2018, vol. 2018-Augus, pp. 984–989.

[18] N. T. Pickle, J. M. Wilken, J. M. Aldridge, R. R. Neptune, and A. K. Silverman, “Whole-body angular momentum during stair walking using passive and powered lower-limb prostheses.,” *J. Biomech.*, vol. 47, no. 13, pp. 3380–9, Oct. 2014.

[19] T. C. Pataky, “One-dimensional statistical parametric mapping in Python,” *Comput. Methods Biomech. Biomed. Engin.*, vol. 15, no. 3, pp. 295–301, 2012.

[20] L. A. Nolasco, A. K. Silverman, and D. H. Gates, “Whole-body and segment angular momentum during 90-degree turns.,” *Gait Posture*, vol. 70, no. February, pp. 12–19, 2019.

[21] K. Honda, Y. Sekiguchi, T. Muraki, and S. I. Izumi, “The differences in sagittal plane whole-body angular momentum during gait between patients with hemiparesis and healthy people,” *J. Biomech.*, vol. 86, pp. 204–209, 2019.

[22] H. B. Frame, C. Finetto, J. C. Dean, and R. R. Neptune, “The influence of lateral stabilization on walking performance and balance control in neurologically-intact and post-stroke individuals,” *Clin. Biomech.*, vol. 73, no. February 2019, pp. 172–180, 2020.

[23] N. Pickle, S. Shearin, and N. Fey, “Dynamic neural network approach to targeted balance assessment of individuals with and without neurological disease during non-steady-state locomotion,” *J. Neuroeng. Rehabil.*, vol. 16, no. 1, pp. 1–9, 2019.