Muscle Function and Coordination of Stair Ascent

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Stair ascent is an activity of daily living and necessary for maintaining independence in community environments. One challenge to improving an individual's ability to ascend stairs is a limited understanding of how lower-limb muscles work in synergy to perform stair ascent. Through dynamic coupling, muscles can perform multiple functions and require contributions from other muscles to perform a task successfully. The purpose of this study was to identify the functional roles of individual muscles during stair ascent and the mechanisms by which muscles work together to perform specific subtasks. A three-dimensional (3D) muscle-actuated simulation of stair ascent was generated to identify individual muscle contributions to the biomechanical subtasks of vertical propulsion, anteroposterior (AP) braking and propulsion, mediolateral control and leg swing. The vasti and plantarflexors were the primary contributors to vertical propulsion during the first and second halves of stance, respectively, while gluteus maximus and hamstrings were the primary contributors to forward propulsion during the first and second halves of stance, respectively. The anterior and posterior components of gluteus medius were the primary contributors to medial control, while vasti and hamstrings were the primary contributors to lateral control during the first and second halves of stance, respectively. To control leg swing, antagonistic muscles spanning the hip, knee, and ankle joints distributed power from the leg to the remaining body segments. These results compliment previous studies analyzing stair ascent and provide further rationale for developing targeted rehabilitation strategies to address patient-specific deficits in stair ascent. [DOI: 10.1115/1.4037791]

1 Introduction

Stair ascent is a common activity of daily living and necessary for maintaining independence in home and community environments. However, stair ascent can be more biomechanically challenging than level walking. Compared to level walking where the center-of-mass (COM) is predominantly propelled horizontally, stair ascent requires an individual to propel the COM both horizontally and significantly more vertically [1,2] while controlling mediolateral motion and leg swing [1,2]. Appropriate leg swing is important to avoid contact with the intermediate step and facilitate proper foot placement. As a result, several studies have observed increased lower-limb joint demands (e.g., see Refs. [1] and [3]), energy cost [4,5], and knee contact forces [6] during stair ascent relative to level walking. In addition, previous work has shown that dynamic balance is more difficult to maintain during stair ascent than during level walking [7]. These differences suggest that stair ascent likely requires altered muscle contributions relative to level walking.

A number of insightful experimental studies have analyzed net joint moments [8,9], powers [9–11], and work [11] during stair ascent and have identified the knee extensor (e.g., see Refs. [9–11]) and plantarflexor [8,10,11] groups as important contributors with secondary contributions from the hip abductor group [8,9]. These studies provide a detailed understanding of the biomechanics of stair ascent at the joint level.

Others have sought to understand muscle contributions to stair ascent at the individual muscle level by correlating electromyographic (EMG) data with kinematic and kinetic data (e.g., see Ref. [1]) and similarly identified the knee extensor, ankle plantarflexor, and hip abductor groups as important contributors to stair ascent. These studies identified important differences in muscle excitation intensity and timing that occur during stair ascent. However, the complex nonlinear relationships between muscle excitation and resulting force in addition to dynamic coupling, which allows a muscle to accelerate joints and segments it does not span, makes identifying muscle contributions to a given biomechanical task challenging [12,13].

Musculoskeletal modeling and simulation techniques utilize explicit equations for the neuromuscular and musculoskeletal system dynamics which allow quantification of the causal relationships between muscle excitation inputs and resulting task performance. Previous studies have used simulations to identify individual muscle contributions to tasks such as walking (e.g., see Refs. [14–16]), running (e.g., see Refs. [17] and [18]), pedaling (e.g., Refs. [19] and [20]), and wheelchair propulsion (e.g., see Ref. [21]). Recently, Lin et al. [22] performed a simulation analysis to determine the contributions of five muscle groups to body support, forward propulsion, and balance control during stair ascent by analyzing whole-body COM accelerations.

The purpose of this study was to build upon these previous studies by identifying the contributions of individual muscles to vertical propulsion, anteroposterior (AP) braking and propulsion, mediolateral control, and leg swing during stair ascent and the biomechanical mechanisms by which individual muscles work in synergy to perform these subtasks. Specifically, we seek to identify how muscles generate, absorb, and/or transfer mechanical power between body segments to accelerate the whole-body COM. These results will contribute further to our understanding of muscle coordination during stair ascent and provide additional insight for the development of effective, targeted rehabilitation programs aimed at improving an individual's ability to ascend stairs.

2 Methods

2.1 Musculoskeletal Model. A previously developed three-dimensional (3D) bipedal musculoskeletal model [23] was adapted to simulate stair ascent. The model was developed using SIMM/Dynamics Pipeline (MusculoGraphics, Inc., Santa Rosa, CA) and consisted of 14 rigid body segments representing the head-arms-trunk, pelvis, and bilaterally the thigh, shank, patella, talus, calcaneus and toes. The model had 23 degrees-of-freedom (DOF) with a 6DOF (three translations, three rotations) joint

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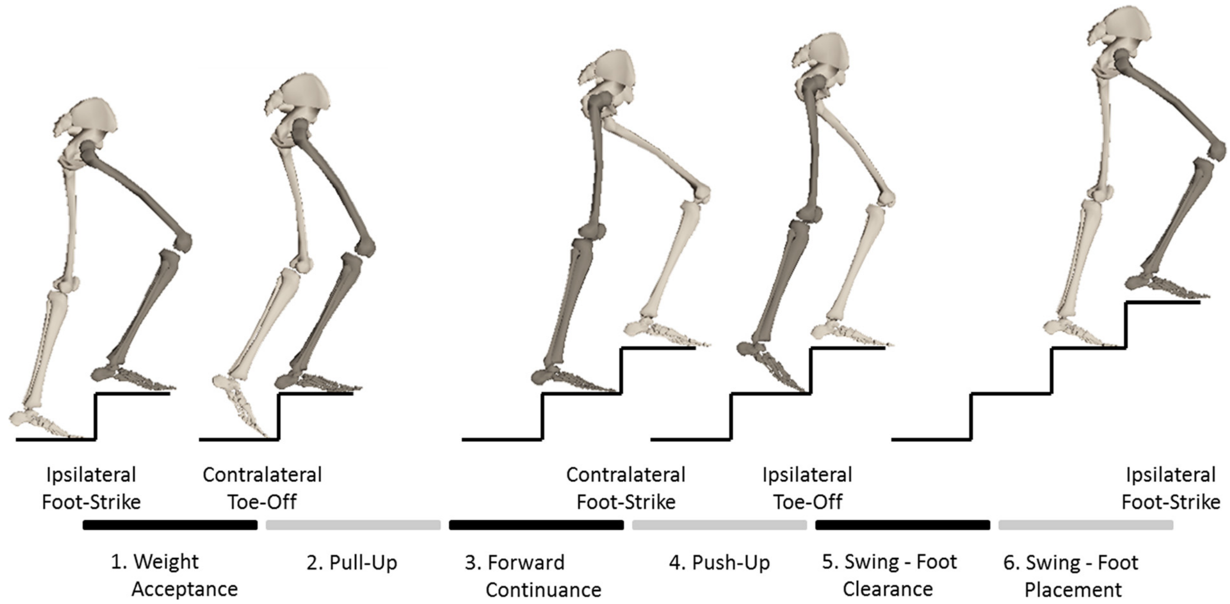

Fig. 1 The six regions of the ipsilateral (dark shaded) leg gait cycle: (1) weight acceptance (ipsilateral foot-strike to contralateral toe-off), (2) pull-up and (3) forward continuance (contralateral toe-off to contralateral foot-strike divided into two equal sections), (4) push-up (contralateral foot-strike to ipsilateral toe-off), (5) early swing and foot clearance and (6) late swing and foot placement (ipsilateral toe-off to ipsilateral foot-strike divided into two equal sections). The six regions of the gait cycle were adapted from previous studies [1,10].

between the pelvis and the ground, a 3DOF spherical joint between the trunk and the pelvis, a 3DOF spherical joint for each hip, and 1DOF revolute joints at each knee, ankle, subtalar, and metatarsal joint. Passive torques representing the forces applied by passive tissues and structures in the joints, including ligaments, were applied at each joint [24]. Foot-ground contact was modeled using 31 viscoelastic elements with Coulomb friction attached to each foot and evenly distributed across the calcaneus and toes [25]. The height of the ground in the foot-ground contact model was modified to represent the surface of the stairs (Rise/Run: 0.1778 m/0.2794 m). The dynamical equations of motion were generated using SD/FAST (PTC, Needham, MA).

The model was driven by 38 Hill-type musculotendon actuators per leg. Muscle excitations at time t ($e(t)$, Eq. (1)) for the 38 musculotendon actuators were defined using bimodal excitation patterns with three parameters to be optimized for each mode (i) including the *onset*, *offset*, and amplitude (A)

$$e(t)=\sum_{i=1}^{2}\begin{cases}\dfrac{A_i}{2}\left(1-\cos\left(\dfrac{2\pi(t-\text{onset}_i)}{\text{offset}_i-\text{onset}_i}\right)\right) & \text{onset}_i\le t\le \text{offset}_i\\ 0 & t<\text{onset}_i\,||\,t>\text{offset}_i\end{cases} \tag{1}$$

Bimodal excitation patterns were allowed for each muscle but not required, giving the optimization algorithm freedom to select a unimodal pattern when appropriate.

Muscle contraction dynamics were governed by intrinsic force-length-velocity relationships [26]. Muscle activation and deactivation dynamics were modeled using a nonlinear first-order differential equation [20] with previously derived [27] activation and deactivation time constants (see Table SM1, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection).

2.2 Dynamic Optimization. The dynamic optimization framework (see Fig. SM1, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection) used a simulated annealing optimization algorithm [28] to identify the six excitation parameters for each muscle that minimized the following objective function (J) to produce an optimal simulation:

$$J=\sum_{i=1}^{n_{\text{step}}}\left(\sum_{j=1}^{n_{\text{vars}}}wt_j\frac{\left(Y_{ij}-\hat{Y}_{ij}\right)^2}{\text{SD}_{ij}^2}+ws\sum_{k=1}^{n_{\text{musc}}}\left(\frac{F_{ik}}{A_k}\right)^2\right) \tag{2}$$

where n_{step} is the number of time steps, n_{vars} is the number of quantities evaluated, including joint angles, pelvis translations, and ground reaction forces (GRFs), n_{musc} is the number of muscles, Y_{ij} is the experimental value at time step i for quantity j, $\hat{Y}_{ij}$ is the simulated value, SD_{ij} is the experimental standard deviation (SD) of quantity j at time step i, F_{ik} is the muscle force at time step i for muscle k, A_k is the physiological cross-sectional area of muscle k, wt_j is the weighting for the difference in quantity j, and ws is the weighting for muscle stress. The first component of the objective function minimized the differences between simulated and experimental joint kinematics and GRFs, while the second component minimized total muscle stress to minimize unnecessary muscle co-contraction. The values for wt_j were adjusted during the optimization process to emphasize parameters that needed to be improved while the value for ws was adjusted so that muscle stress represented approximately 25% of the overall objective function value (J).

2.3 Simulation Analyses. To identify the individual muscle contributions to the biomechanical subtasks of vertical propulsion, anteroposterior braking and propulsion, mediolateral control, and leg swing, and the mechanisms by which individual muscles work in synergy to achieve these subtasks, previously described GRF decomposition and segment power analyses were performed [29,30]. The contribution of each muscle to vertical propulsion, anteroposterior braking and propulsion, and mediolateral control was quantified by its contribution to the vertical, anteroposterior, and mediolateral (ML) GRFs, respectively, during the first (weight acceptance through pull-up, Fig. 1) and second (forward continuance through push-up, Fig. 1) halves of stance. Muscle function was further investigated through a segment power analysis by examining the mechanical power generated, absorbed, and/or transferred by each muscle to the trunk, ipsilateral leg, and

Table 1 Muscles included in the musculoskeletal model and their corresponding analysis group

Muscles	Analysis groups
Iliacus Psoas	IL
Adductor longus Adductor brevis Pectineus Quadratus femoris	AL
Superior adductor magnus Middle adductor magnus Inferior adductor magnus	AM
Sartorius	SAR
Rectus femoris	RF
Vastus medialis Vastus lateralis Vastus intermedius	VAS
Anterior gluteus medius Middle gluteus medius Anterior gluteus minimus Middle gluteus minimus	GMEDA
Posterior gluteus medius Posterior gluteus minimus Piriformis Gemellus	GMEDP
Tensor fasciae latae	TFL
Superior gluteus maximus Middle gluteus maximus Inferior gluteus maximus	GMAX
Semitendinosus Semimembranosus Gracilis Biceps femoris long head	HAM
Biceps femoris short head	BFSH
Medial gastrocnemius Lateral gastrocnemius	GAS
Soleus Tibialis posterior Flexor digitorum longus	SOL
Tibialis anterior Extensor digitorum longus	TA

contralateral leg during stance in the vertical, AP and ML directions (defined as vertical, anteroposterior, and mediolateral power, respectively). To quantify each muscle's contribution to leg swing, the power delivered to the leg during swing initiation (push-up, Fig. 1), early swing (swing-foot clearance, Fig. 1), and late swing (swing-foot placement, Fig. 1) was determined. Muscles with similar function were combined into 15 muscle groups for the analyses (Table 1), with the contributions within each group being summed. The contribution of gravity to vertical propulsion, anteroposterior braking and propulsion, mediolateral control, and leg swing was also computed since it has been shown to be important in level walking [31,32].

2.4 Experimental Data. Experimental data were necessary to provide group-averaged target kinematic and kinetic data used by the optimization framework to produce a simulation consistent with normal stair ascent mechanics. Twenty-seven subjects (15 female; 21.9 ± 4.3 years; 73.0 ± 15.0 kg; 1.7 ± 0.1 m) without pain or history of major lower extremity injury participated in this study, which was approved by the Institutional Review Board at Brooke Army Medical Center (Fort Sam Houston, San Antonio, TX). After obtaining written informed consent, subjects ascended a 16-step (Rise/Run: 0.1778 m/0.2794 m) instrumented staircase (AMTI, Inc., Watertown, MA) in a step-over-step manner at a fixed cadence (80 steps per minute). GRF data were collected from forceplates (1200 Hz, AMTI, Inc., Watertown, MA) embedded in steps 5–8. A 26-camera optoelectronic motion capture system (120 Hz, Motion Analysis Corp., Santa Rosa, CA) and a body segment marker set with 57 reflective markers were used to collect three-dimensional whole-body kinematics [33]. In addition, a digitization process was used to identify 20 bilateral anatomical bony landmarks (C-motion, Inc., Germantown, MD). For reference, these experimental data (including three additional subjects) have been previously published [34].

All biomechanical data were processed in VISUAL3D (C-motion, Inc., Germantown, MD). A 13-segment model was created and scaled to each subject's body mass and height [35] using the anatomical landmarks to define the joint centers and joint coordinate systems recommended by the International Society of Biomechanics [36–38]. A low-pass, fourth-order Butterworth filter was applied to the marker and GRF data with cut-off frequencies of 6 Hz and 50 Hz, respectively. GRFs were normalized by subject body weight and joint kinematics were computed using Euler angles with pelvis, hip, knee, and ankle kinematics defined using previously determined Cardan rotation sequences [36,38,39]. For each subject, GRFs as well as three-dimensional joint kinematics corresponding to five complete gait cycles for each limb were time-normalized to 100% of the gait cycle and exported to MATLAB (MathWorks, Inc., Natick, MA). In MATLAB, the GRFs and joint kinematics were averaged across gait cycles and subjects for each limb.

3 Results

3.1 Simulation Quality. The optimization framework identified a set of muscle excitations that successfully emulated the experimental kinematics and GRFs, with most quantities within two SDs of the experimental data. Thus, overall the simulation fell within a normal distribution of the experimental data, and therefore, was considered consistent with normal stair ascent mechanics. The average root-mean-square error between the simulated and experimental pelvis translations, joint kinematics, and GRFs across the gait cycle was 0.023 m (2 SDs = 0.081 m), 6.30 deg (2 SDs = 10.05 deg), and 0.063% body weight (2 SDs = 0.069%BW), respectively (see Supplementary Video, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection). In addition, the timing profiles for the optimized muscle excitations (see Fig. SM2, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection) compared well with EMG data available in the literature [1,40–42].

3.2 Vertical Propulsion. During the first half of ipsilateral leg stance (Fig. 1: weight acceptance through pull-up), VAS was the primary contributor to vertical propulsion of the body COM, with additional contributions from GMAX, SOL, GMEDP, and GMEDA (Fig. 2; see Table 1 for muscle group abbreviations). Gravity was also a large contributor to the vertical GRF (Fig. 2). To propel the COM vertically, both VAS and SOL generated power in the vertical direction to the trunk and ipsilateral leg (Fig. 3). Concurrently, GMAX generated power to the trunk while it also transferred power from the contralateral leg to the trunk (Fig. 3). Both GMEDA and GMEDP generated power to the trunk

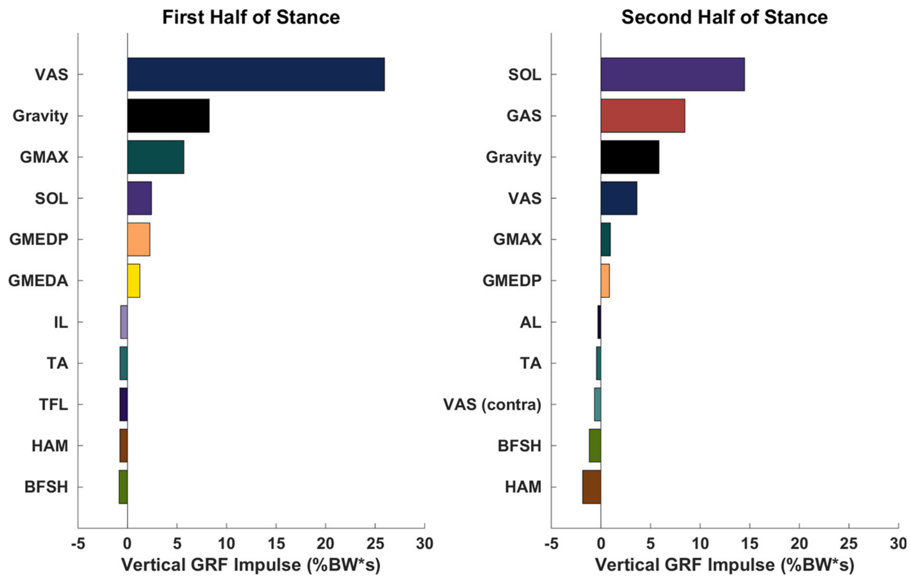

Fig. 2 Primary positive and negative contributors to vertical propulsion of the body COM (i.e., the vertical GRF impulse) during the two halves of ipsilateral stance: (1) weight acceptance through pull-up, and (2) forward continuance through push-up. Unless otherwise specified, muscles are from the ipsilateral leg. For muscle group abbreviations, see Table 1.

and contralateral leg, and transferred power from the ipsilateral leg to the trunk and contralateral leg (Fig. 3).

During the second half of ipsilateral leg stance (Fig. 1: forward continuance through push-up), the plantarflexors (SOL and GAS) were the primary contributors to vertical propulsion with additional contributions from VAS, while HAM opposed vertical propulsion (Fig. 2). Gravity was also a critical contributor to the vertical GRF (Fig. 2). SOL, GAS, and VAS all generated power directly to the trunk and ipsilateral leg (Fig. 3). VAS's contribution decreased to zero around contralateral foot-strike (~50% ipsilateral gait cycle) after reaching its peak during the first half of stance, whereas SOL and GAS contributed to vertical propulsion

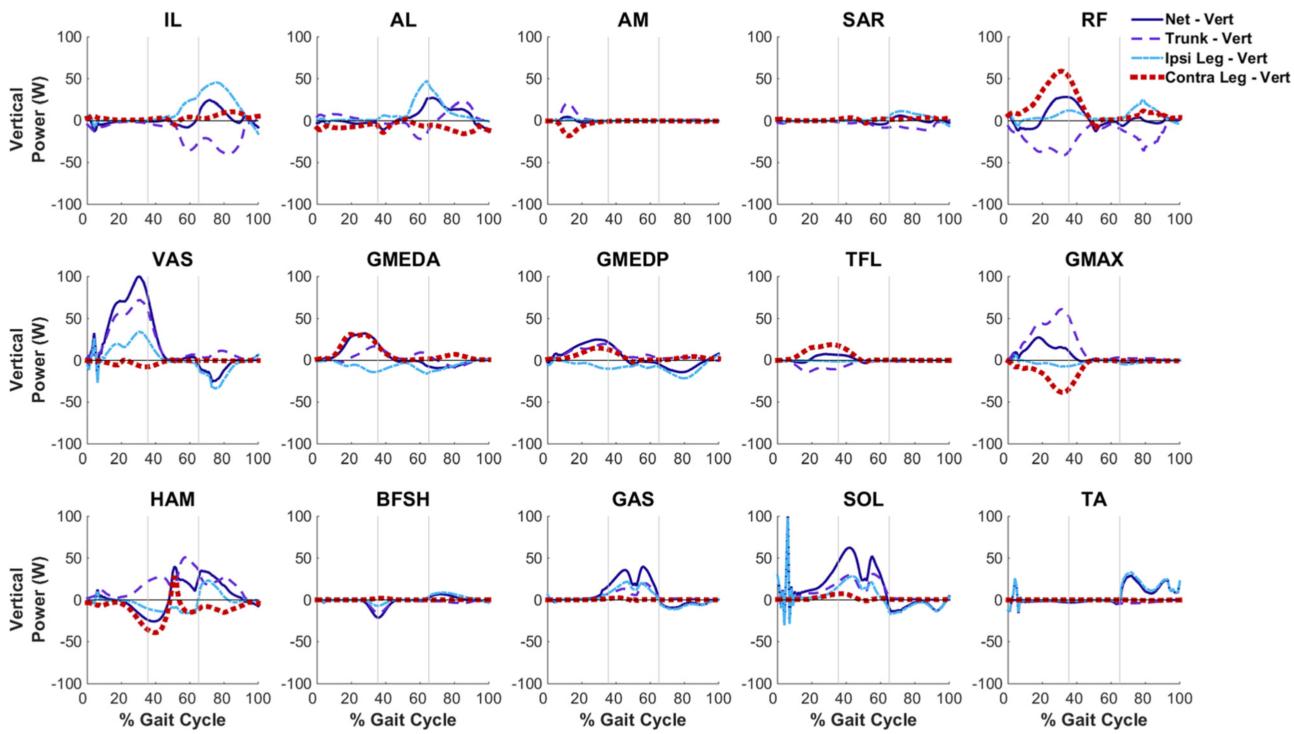

Fig. 3 Musculotendon mechanical power output from the ipsilateral leg muscles across the ipsilateral gait cycle and distributed to the trunk, ipsilateral (Ipsi) leg, and contralateral (Contra) leg in the vertical direction (vertical power). Positive (negative) net values indicate power generated (absorbed) by the musculotendon actuator. Positive (negative) values for the leg or trunk indicate that power is being generated to (absorbed from) the leg or trunk which is being accelerated (decelerated) in the direction of its motion. The gray lines divide the gait cycle into three regions: (1) weight acceptance through pull-up, (2) forward continuance through push-up, and (3) swing (foot clearance through foot placement). For muscle group abbreviations, see Table 1. Note that the large, transient spikes in SOL's power at the beginning of the gait cycle arise due to the force impulse generated at foot-strike.

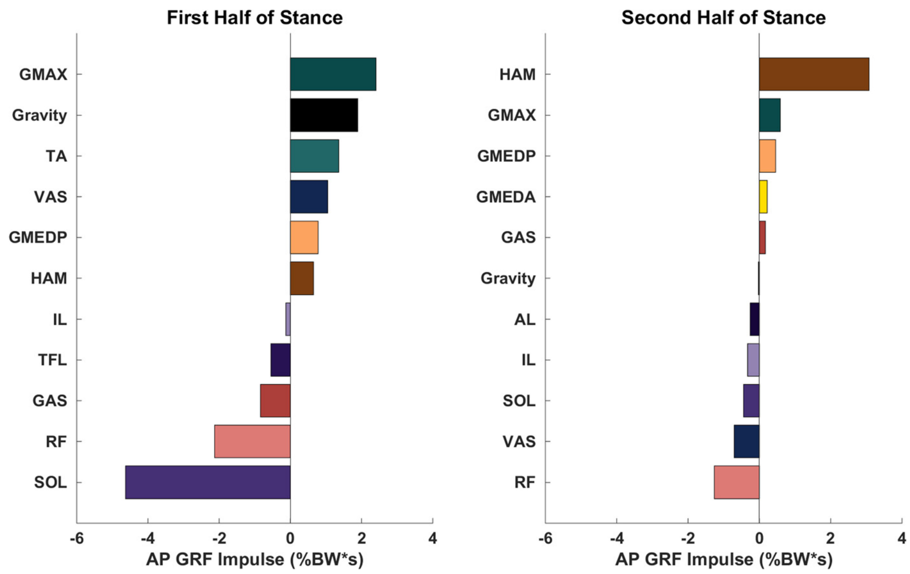

Fig. 4 Primary positive and negative contributors to AP braking and propulsion of the body COM (i.e., the AP GRF impulse) during the two halves of ipsilateral stance: (1) weight acceptance through pull-up, and (2) forward continuance through push-up. Positive (negative) GRF impulses indicate contributions to forward propulsion (braking) of the COM. Muscles are from the ipsilateral leg. For muscle group abbreviations, see Table 1.

throughout the entire second half of stance. Prior to contralateral foot-strike (~50% ipsilateral gait cycle), HAM absorbed power from the legs while also redistributing some of the power from the legs to the trunk (Fig. 3). Following contralateral foot-strike, HAM began generating power to the trunk, although it continued to redistribute power from the legs to the trunk (Fig. 3). The power HAM delivered to the trunk was not enough to overcome its power absorption from both legs, causing HAM to ultimately decrease vertical propulsion.

3.3 Anteroposterior Braking and Propulsion. During the first half of ipsilateral leg stance, GMAX, gravity, TA, VAS, GMEDP, and HAM were the primary contributors to forward propulsion of the body COM, while SOL was the primary contributor to braking the body COM with additional contributions from RF, GAS, and tensor fasciae latae (TFL) (Fig. 4). GMAX, TA, GMEDP, and HAM all contributed to forward propulsion by generating or transferring power in the AP direction to one or both legs (Fig. 5). GMAX and HAM generated power to both legs and transferred power from the trunk to the legs, while TA generated power directly to the ipsilateral leg (Fig. 5). GMEDP absorbed power from the contralateral leg and trunk, and redistributed some of this power to the ipsilateral leg (Fig. 5). Unlike the other primary contributors, GMEDP absorbed net power in the AP direction. However, by transferring a significant amount of power from the trunk to the ipsilateral leg, GMEDP ultimately contributed to forward propulsion (Fig. 5). Of the primary contributors to forward propulsion, VAS alone contributed to forward propulsion by generating power to the trunk and transferring power from the legs to the trunk (Fig. 5). The forward propulsion generated by these muscle groups partially counteracted the muscles contributing to braking in the first half of stance (net negative AP GRF). In this region, SOL and GAS absorbed power directly from the ipsilateral leg (Fig. 5). In addition, RF and TFL absorbed power from both legs, primarily the contralateral leg, and transferred some of this power to the trunk. However, the power transferred to the trunk was not enough to overcome RF and TFL's absorption of power from both legs (Fig. 5).

During the second half of ipsilateral leg stance, HAM was the primary contributor to forward propulsion, while RF and VAS were the primary contributors to braking (Fig. 4). Gravity also contributed to braking, but to a lesser extent (Fig. 4). HAM generated power directly to both the ipsilateral and contralateral legs, and transferred a significant amount of power from the trunk to the legs (Fig. 5). While this decreased the trunk AP power, HAM ultimately contributed to forward propulsion by generating greater power to the legs. In addition, while SOL was not a primary contributor to the AP GRF in this region, it played a critical role in redistributing power from the ipsilateral leg to the trunk (Fig. 5). Similar to the first half of stance, RF continued to absorb power from both legs while transferring power from the legs to the trunk (Fig. 5). However, contrary to the first half of stance, VAS switched from generating to absorbing net power, ultimately absorbing power from the ipsilateral leg while transferring some power from the ipsilateral leg to the trunk (Fig. 5). As a result, while both RF and VAS redistributed some power to the trunk to propel it forward, it was not enough to overcome their contributions to leg braking.

3.4 Mediolateral Control. In general, all contributions to mediolateral control were smaller than the contributions to vertical and anteroposterior braking and propulsion. During the first half of ipsilateral leg stance when the COM moves first laterally over the ipsilateral leg and then medially [2], VAS was the primary contributor to lateral (positive) control of the COM, while GMEDA was the primary contributor to medial (negative) control with additional contributions from GMEDP (Fig. 6). In addition, gravity contributed to lateral control (Fig. 6). VAS absorbed power in the ML direction from the trunk and transferred some power from the trunk to the contralateral leg (Fig. 7). While this decelerated the trunk's lateral motion, it accelerated the contralateral leg's medial motion which accelerated the overall body COM laterally. GMEDA generated power to the trunk and initially transferred power from the ipsilateral leg to the trunk prior to generating power to the ipsilateral leg (Fig. 7). While this accelerated the trunk laterally, it also decelerated and then accelerated the ipsilateral leg's lateral and medial motion, respectively. In contrast, GMEDP absorbed power from the trunk and initially transferred power from the trunk to the ipsilateral leg before absorbing power from the ipsilateral leg (Fig. 7), decelerating the trunk's lateral motion while also accelerating and then decelerating the ipsilateral leg's lateral and medial motion, respectively.

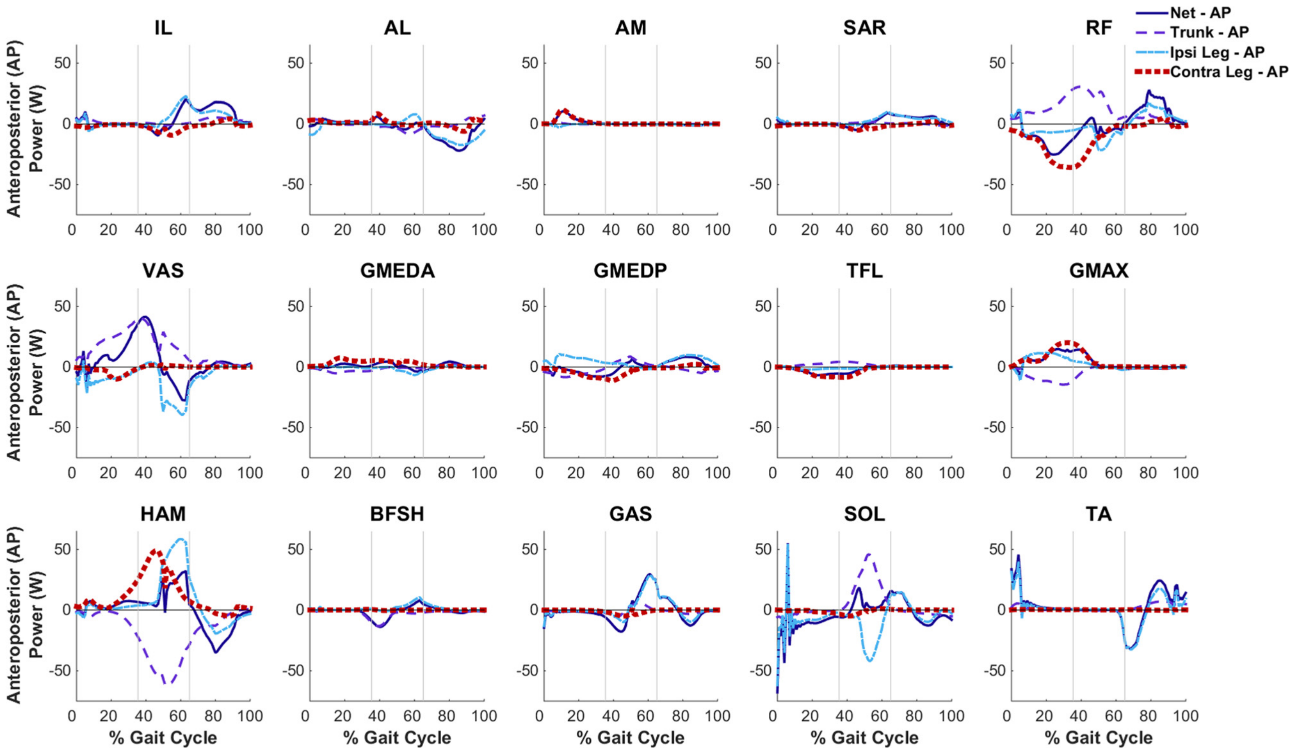

Fig. 5 Musculotendon mechanical power output from the ipsilateral leg muscles across the ipsilateral gait cycle and distributed to the trunk, ipsilateral (Ipsi) leg, and contralateral (Contra) leg in the AP direction (AP power). Positive (negative) net values indicate power generated (absorbed) by the musculotendon actuator. Positive (negative) values for the leg or trunk indicate that power is being generated to (absorbed from) the leg or trunk which is being accelerated (decelerated) in the direction of its motion. The gray lines divide the gait cycle into three regions: (1) weight acceptance through pull-up, (2) forward continuance through push-up, and (3) swing (foot clearance through foot placement). For muscle group abbreviations, see Table 1. Note that the large, transient spikes in SOL's power at the beginning of the gait cycle arise due to the force impulse generated at foot-strike.

During the second half of ipsilateral leg stance when the COM moves first laterally onto the contralateral limb and then medially again [2], HAM was the primary contributor to lateral (positive) control with additional contributions from AL, while GMEDP and GMEDA remained primary contributors to medial (negative) control with additional contributions from RF (Fig. 6). Gravity also contributed to medial control (Fig. 6). Most of the power generated, absorbed, or transferred in the ML direction by the muscles

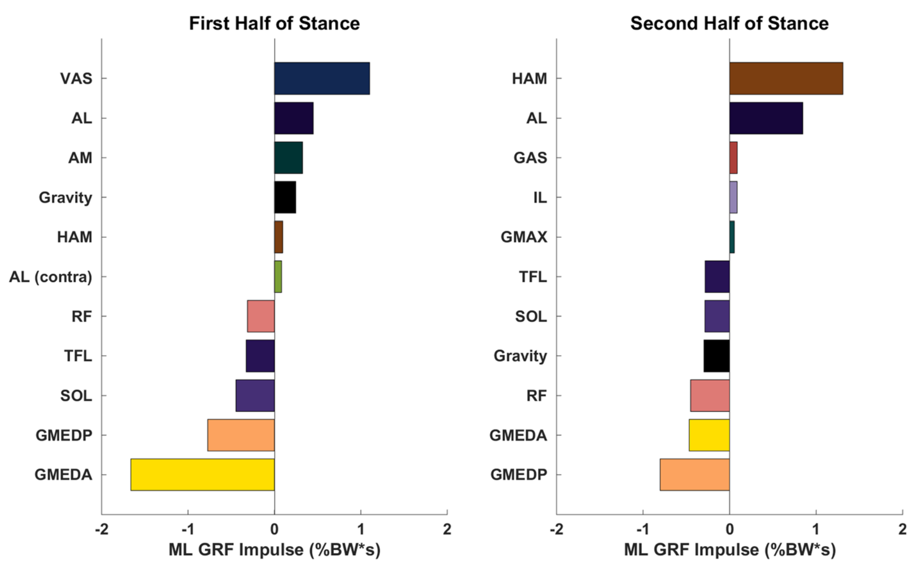

Fig. 6 Primary positive and negative contributors to mediolateral (ML) control of the body COM (i.e., the ML GRF impulse) during the two halves of ipsilateral stance: (1) weight acceptance through pull-up and (2) forward continuance through push-up. Positive (negative) GRF impulses indicate contributions to lateral (medial) control of the COM. Unless otherwise specified, muscles are from the ipsilateral leg. For muscle group abbreviations, see Table 1.

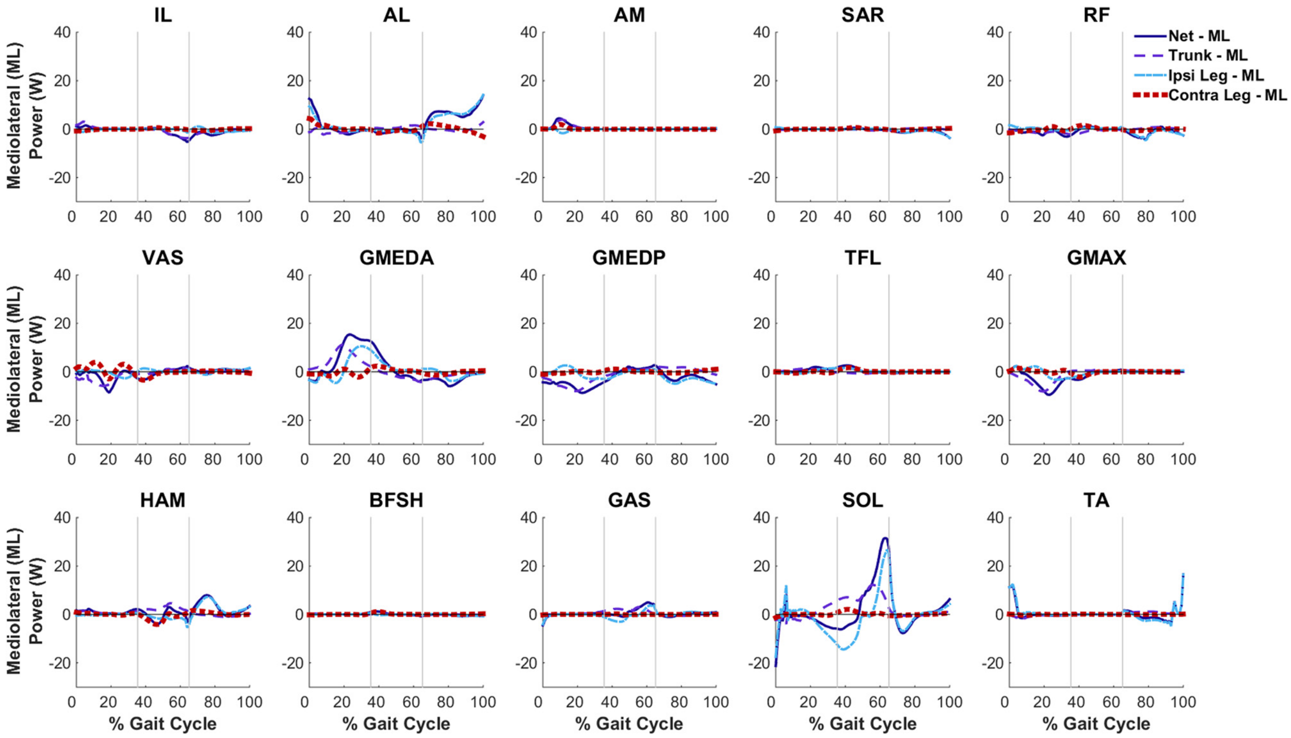

Fig. 7 Musculotendon mechanical power output from the ipsilateral leg muscles across the ipsilateral gait cycle and distributed to the trunk, ipsilateral (Ipsi) leg, and contralateral (Contra) leg in the mediolateral (ML) direction (mediolateral power). Positive (negative) net values indicate power generated (absorbed) by the musculotendon actuator. Positive (negative) values for the leg or trunk indicate that power is being generated to (absorbed from) the leg or trunk which is being accelerated (decelerated) in the direction of its motion. The gray lines divide the gait cycle into three regions: (1) weight acceptance through pull-up, (2) forward continuance through push-up, and (3) swing (foot clearance through foot placement). For muscle group abbreviations, see Table 1. Note that the large, transient spikes in SOL's power at the beginning of the gait cycle arise due to the force impulse generated at foot-strike.

in this region was very small. However, one notable exception was SOL. While SOL was not a major contributor to medial control, it absorbed and then generated a substantial amount of power to the ipsilateral leg in addition to generating power to the trunk (Fig. 7). This simultaneously decelerated the ipsilateral leg's medial motion while accelerating the trunk's medial motion and then accelerated both the trunk and the ipsilateral leg's lateral motion.

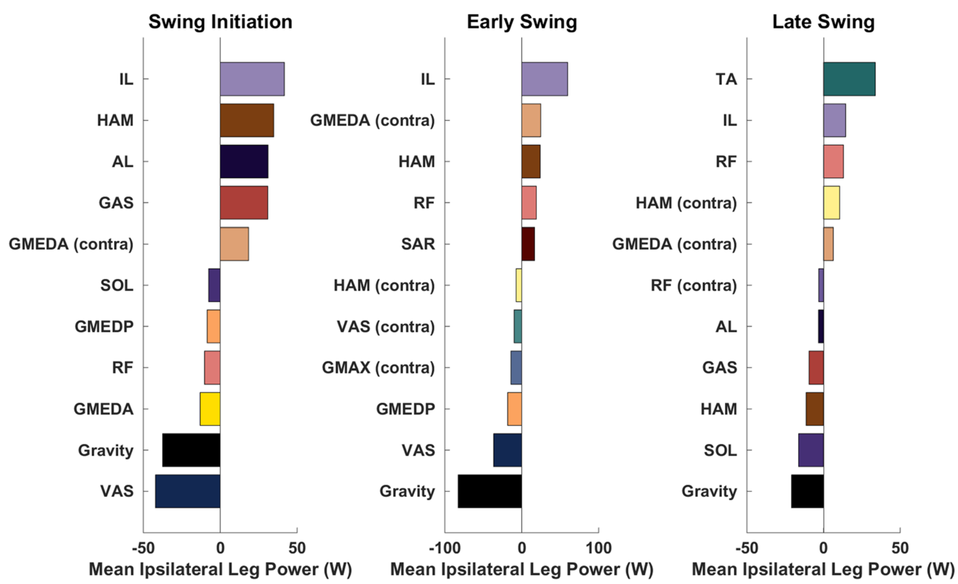

Fig. 8 Primary contributors to net mean mechanical power generation (positive) to and absorption (negative) from the ipsilateral leg during (1) swing initiation (push-up), (2) early swing (foot clearance), and (3) late swing (foot placement). Unless otherwise specified, muscles are on the ipsilateral side. For muscle group abbreviations, see Table 1. Note the different scale in early swing.

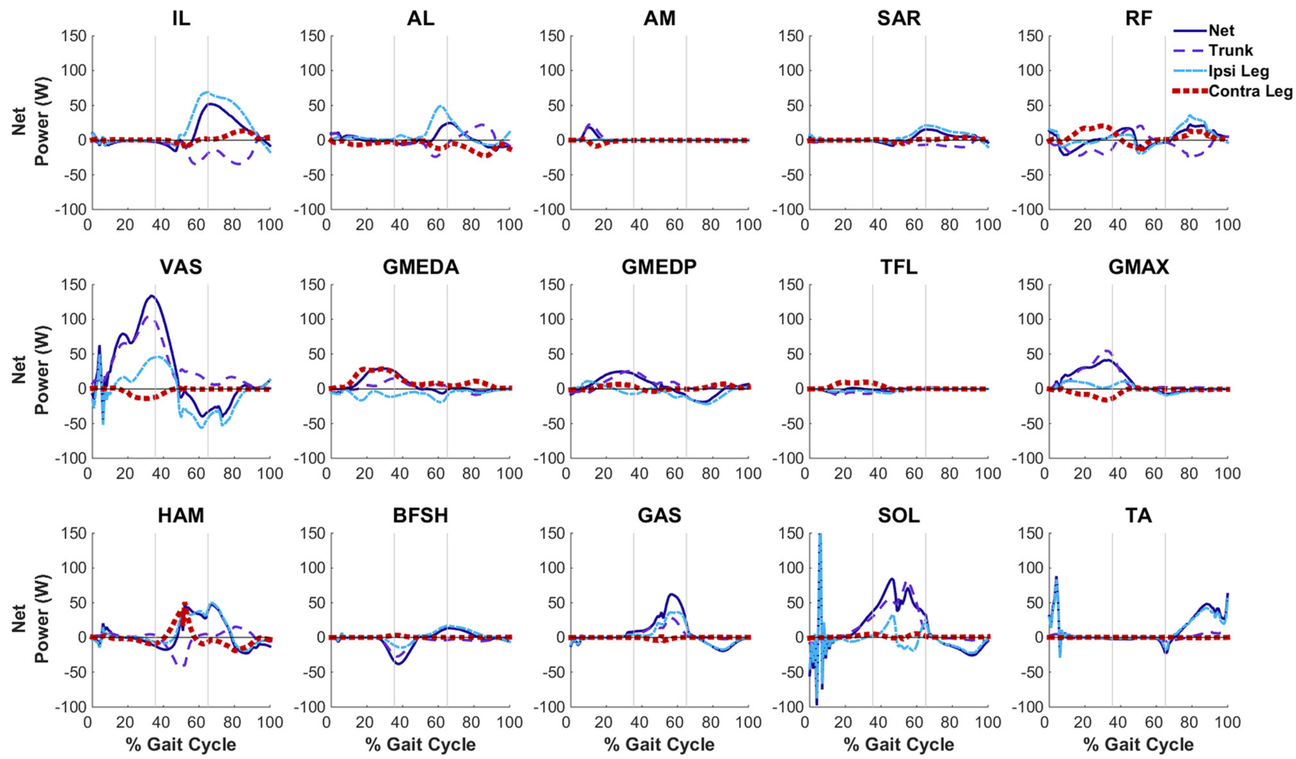

Fig. 9 Net musculotendon mechanical power output from the ipsilateral leg muscles across the ipsilateral gait cycle and distributed to the trunk, ipsilateral (Ipsi) leg, and contralateral (Contra) leg. Positive (negative) net values indicate power generated (absorbed) by the musculotendon actuator. Positive (negative) values for the leg or trunk indicate that power is being generated to (absorbed from) the leg or trunk which is being accelerated (decelerated) in the direction of its motion. The gray lines divide the gait cycle into three regions: (1) weight acceptance through pull-up, (2) forward continuance through push-up, and (3) swing (foot clearance through foot placement). For muscle group abbreviations, see Table 1. Note that the large, transient spikes in SOL's power at the beginning of the gait cycle arise due to the force impulse generated at foot-strike.

3.5 Leg Swing. During ipsilateral leg swing initiation (Fig. 1: push-up), ipsilateral IL, HAM, AL, and GAS in addition to contralateral GMEDA were the primary generators of power to the ipsilateral leg (Fig. 8). Both IL and AL generated power directly to the ipsilateral leg and transferred power from the trunk to the ipsilateral leg, while GAS and HAM generated power to the ipsilateral leg and GAS generated power to the trunk as well (Fig. 9). Contralateral GMEDA also generated power directly to the ipsilateral leg while redistributing power from the contralateral leg to the ipsilateral leg (Fig. 9: 0–18% gait cycle-contralateral leg is in weight acceptance phase; contralateral and ipsilateral legs are reversed). Gravity as well as ipsilateral VAS were the primary absorbers of power from the ipsilateral leg during swing initiation (Fig. 8), with VAS absorbing power from the ipsilateral leg and transferring power from the ipsilateral leg to the trunk (Fig. 9). In early swing (Fig. 1: swing-foot clearance), ipsilateral IL remained the primary generator of power to the ipsilateral leg, while gravity and ipsilateral VAS remained the primary absorbers of power (Fig. 8). These muscles continued to contribute to leg swing as they had during swing initiation (Fig. 9).

During late swing (Fig. 1: swing-foot placement), the primary contributors were partially altered compared to swing initiation and early swing, with ipsilateral IL still generating a large amount of power to the ipsilateral leg but TA and RF also generating a substantial amount of power to the ipsilateral leg (Fig. 8). IL and RF generated power to the ipsilateral leg and, to a lesser extent, the contralateral leg, while also transferring power from the trunk to the legs (Fig. 9). Concurrently, TA generated power to the ipsilateral leg (Fig. 9). Gravity as well as the ipsilateral plantarflexors (SOL and GAS) and HAM were the primary contributors to power absorption from the ipsilateral leg in preparation for foot contact (Fig. 8). All three muscle groups absorbed power from the ipsilateral leg in preparation for contact with the ground, while HAM also transferred power from the legs to the trunk (Fig. 9).

4 Discussion

Stair ascent and descent are common activities of daily living needed to maintain independence in both the home and community. Compared to stair descent, stair ascent is a more strenuous activity [43] requiring greater muscle activation [1,44,45], net joint work [11], and metabolic energy [4]. As a result, individuals with various lower-limb impairments (e.g., Refs. [46–48]) often utilize compensatory mechanisms to ascend stairs. In addition, older or elderly individuals often develop alternate methods for stair ascent to compensate for functional deficits that arise due to aging (e.g., see Ref. [49]). Understanding the contributions of individual muscles to stair ascent provides the foundation for understanding the compensatory mechanisms used in impaired individuals and developing effective rehabilitation techniques to help restore mobility. Thus, the goal of this study was to understand how muscles work in synergy to perform stair ascent by analyzing a muscle-actuated forward dynamics simulation of stair ascent and quantifying each muscle's contribution to vertical propulsion, anteroposterior braking and propulsion, mediolateral control, and leg swing.

In general, several key muscle groups were found to be the primary contributors through their generation and redistribution of mechanical power among the body segments (e.g., see Ref. [13]), which acted to propel the body vertically and anteroposteriorly, control mediolateral motion, and facilitate leg swing.

4.1 Vertical Propulsion. Throughout stance, vertical propulsion was primarily generated by the knee extensors (VAS) and the plantarflexors (SOL, GAS) with additional contributions from the hip extensors (GMAX) and hip abductors (GMEDP, GMEDA). These results are consistent with previous observations based on EMG timing and joint kinetics that the ipsilateral leg extensors likely provide vertical propulsion [1,41] and with the findings of Lin et al. [22] who identified the contributions of five muscle groups (GMAX, GMED, VAS, SOL, and GAS) to vertical propulsion and found similar contributions. In addition, Wilken et al. [10] identified a correlation between peak knee and ankle joint power and vertical acceleration during the first and second halves of stance, respectively, and Novak and Brouwer [8] identified the plantarflexors and knee extensors as the primary contributors to the support moment with additional contributions from the hip.

Several of the contributors to vertical propulsion also contribute to body support in level walking. Studies have shown that in level walking VAS, GMAX, and GMED are the primary contributors to body support during the first half of stance, while SOL and GAS are the primary contributors during the second half of stance [14,15,30]. The primary difference between body support in level walking and vertical propulsion in stair ascent is the importance of the uniarticular plantarflexors (SOL) in stair ascent during the first half of stance. This difference may be due to several factors including the elevated position of the leading foot, anteriorly shifted center-of-pressure, altered joint kinematics, and the increased demands of propelling the COM vertically in stair ascent compared to supporting the body in level walking. The increased importance of SOL is consistent with previous studies that found increased positive ankle power [9] and work [40] and an increased ankle plantarflexion moment in early stance [9,50] during stair ascent compared to level walking. In the second half of stance, HAM was found to oppose vertical propulsion in stair ascent while significantly contributing to forward propulsion. While this is not the case in level walking [15,30], the hamstrings do have the potential to reduce body support while accelerating the body forward if more muscle force is generated during the second half of stance in level walking [15].

4.2 Anteroposterior Braking and Propulsion. During stance, the hip abductors (GMEDP, TFL), hip extensors (GMAX, HAM), knee extensors (RF, VAS), plantarflexors (SOL, GAS), and dorsiflexors (TA) worked synergistically to control the distribution of AP power to the legs and trunk to achieve anteroposterior braking and propulsion. Lin et al. [22] noted that in the first half of stance, GMAX and GMED contributed to forward propulsion, while SOL and GAS contributed to braking, consistent with the results of the current study. However, contrary to Lin et al. [22], we found that VAS contributed to forward propulsion instead of braking during the first half of stance. During the second half of stance, the contributions from the five muscle groups investigated by Lin et al. [22] were consistent with the results of the current study. Thus, it is possible that differences in the simulated body-segment kinematics (relative to foot placement) between studies may have led to the observed differences in VAS function in early stance.

Similar to level walking, forward progression occurs throughout stair ascent [2]. However, the COM must traverse a shorter distance and the COM AP translation is often coupled with vertical movement leading to differences in muscle function between stair ascent and level walking. In the first half of stance during level walking, HAM contributes to forward propulsion [30], which opposes the braking generated by VAS [15,30], SOL and GAS [14,15,30]. While SOL and GAS remained important contributors to braking in stair ascent, RF and TFL replaced VAS as primary contributors to braking and GMAX, TA, VAS, GMEDA, and GMEDP contributed to forward propulsion instead of HAM. In the second half of stance during level walking, SOL and GAS [14,15] along with GMED [15] contribute to forward propulsion and the knee extensors (RF, VAS) contribute to braking [30]. In stair ascent, HAM became the primary contributor to forward propulsion, while the knee extensors (RF, VAS) remained the primary contributors to braking. These results are consistent with previous work suggesting that during the second half of stance in stair ascent, SOL and GAS are responsible for elevation of the body (vertical propulsion) but are not the main source of AP progression [1].

4.3 Mediolateral Control. To achieve mediolateral control during the first half of stance, the knee extensors (VAS) and hip abductors (GMEDA and GMEDP) were the primary contributors to lateral and medial control, respectively. During the second half of stance, the hip extensors (HAM) and hip adductors (AL) were the primary contributors to lateral control, while the hip abductors (GMEDP, GMEDA) and knee extensors (RF) were the primary contributors to medial control. These results are consistent with Lin et al. [22] who found that VAS contributed to lateral control of the body COM in the first half of stance and GMED contributed to medial control of the body COM throughout stance. They are also consistent with the previous conclusions that the hip abductors pull or balance the body over the limb [1,41] and that abductor moments are important in maintaining the body's COM within the base of support while also countering the destabilizing forces associated with the mass of the trunk and swing leg [51].

Mediolateral control in stair ascent was found to be very similar to level walking. In level walking, VAS, the hip adductors (e.g., AM) [16,52], and HAM [52] contribute to lateral control, all of which also contributed to lateral control in stair ascent. Previously, GMED [16,52] and GMAX [52] were identified as important contributors to medial control in level walking, and in stair ascent, the hip abductors (GMEDA and GMEDP) were found to be the primary contributors to medial control. One notable exception is SOL, which contributes to medial control during stair ascent but lateral control in level walking [16,22,52]. Overall, the similarities in these muscle contributions reflect the similarities in the task of mediolateral control between level walking and stair ascent, which are both straight-line activities where progression is achieved by cyclically alternating between limbs.

4.4 Leg Swing. Throughout leg swing, antagonistic muscles spanning the hip, knee, and ankle (e.g., TA and SOL; HAM; and VAS) acted synergistically to modulate the transfer of power between the trunk, ipsilateral leg, and contralateral leg to achieve controlled leg swing while avoiding contact with the intermediate step through increased limb flexion (i.e., increased ankle dorsiflexion, knee flexion, and/or hip flexion) [1,3,9,41] and hip abduction [9,41] and providing proper foot placement during stair ascent. In addition, compared to the other biomechanical subtasks, leg swing required increased contributions from contralateral leg muscles, likely due to the contralateral limb's role in moving the entire swing leg upward and forward through pelvis motion [1].

Leg swing is a similar task in both stair ascent and level walking with the primary difference being the degree to which the swing leg is flexed [9]. As a result, similar muscles contribute to leg swing in level walking and stair ascent. Similar to level walking [30], GAS and IL played an important role in leg swing initiation during stair ascent. However, while RF is primarily responsible for opposing leg swing initiation in level walking [30], alternative knee extensors (VAS) were primarily responsible in stair ascent, although RF still opposed swing initiation. During early swing in level walking, IL and BFsh accelerate the leg forward [30]. In stair ascent, IL remained the primary contributor, while HAM arose as an important contributor to leg acceleration in place of BFsh. In late swing, while HAM decelerated the leg in preparation for ground contact, consistent with its function in level walking [30], SOL and GAS also became important contributors to leg braking during stair ascent.

4.5 Clinical Relevance. This study provides insight into how individual muscle groups work in synergy to perform the biomechanical subtasks of stair ascent through the generation, absorption, and/or redistribution of mechanical power between the body segments. With this understanding, targeted rehabilitation programs can be designed to increase the force output of specific muscle groups (e.g., through muscle strengthening or increasing neuronal drive) in order to improve the performance of a given subtask or to help compensate for impaired muscle groups. For example, SOL contributes to vertical propulsion, braking, and medial control while also helping to control leg swing. If SOL's force output is impaired, increasing either GAS or VAS output could be an effective intervention to compensate for SOL's contribution to vertical propulsion. VAS could also compensate for SOL's control of leg swing which is essential for appropriate foot placement. However, at times GAS and VAS cannot replicate SOL's contributions to anteroposterior braking and propulsion or mediolateral control, so another muscle would need to compensate. An ideal candidate is RF which contributes to both braking and medial control but does not contribute to vertical propulsion. Therefore, to fully compensate for impaired SOL output, a targeted rehabilitation program could be designed to increase the force output of GAS and/or VAS and RF. Similarly, if specific biomechanical functions are impaired during stair ascent, then understanding the functional roles of individual muscles is useful for designing targeted rehabilitation programs focused on improving the output of muscle groups that perform those specific functions. For example, if an individual is observed to have impaired balance control during stair ascent, then improving the coordination and force output of GMEDA, GMEDP, VAS, and HAM could be an effective intervention.

The results of this study also have important implications for designing effective prosthetic and orthotic devices. For example, when designing a powered ankle-foot prosthesis for stair ascent for transtibial amputees, it would be important to replicate the functions of muscles spanning the ankle joint (e.g., SOL and GAS). However, SOL and GAS contribute oppositely to anteroposterior braking and propulsion (second half of stance), mediolateral control (second half of stance), and swing initiation. Thus, a powered ankle-foot prosthesis may never be able to fully replicate the functions of the ankle plantarflexors due to the unique contributions of the biarticular GAS, and the powered prosthesis may need to be coupled with a targeted rehabilitation program designed to increase the output of muscle groups that can help compensate for GAS and work synergistically with the prosthesis to improve stair ascent for amputees.

4.6 Study Limitations. A principal advantage of musculoskeletal modeling and simulation is that it can provide valuable insight into quantities that cannot be measured experimentally. As a result, the simulation results cannot be directly validated, and therefore, indirect measures of model validation must be used. In this study, two indirect measures were used. First, the optimization algorithm minimized differences between simulated and experimental joint kinematics and GRFs in addition to minimizing muscle stress. By requiring the simulation to closely replicate the human subject experimental data while minimizing muscle co-contraction, a physiologically and biomechanically consistent simulation was produced that closely emulated the walking mechanics of the human subjects. Second, muscle excitation timings were compared to experimental timings available in the literature [1,40–42] to assure that muscles were producing force at the appropriate points in the gait cycle. Although differences were evident (see Fig. SM2, which is available under the "Supplemental Materials" tab for this paper on the ASME Digital Collection), these differences were similar to the variability seen between the experimental studies.

A second potential limitation of musculoskeletal modeling is that some assumptions for musculoskeletal parameters, including segment mass and inertial properties, musculoskeletal geometry, and musculotendon properties, are required. However, the optimization algorithm can compensate for imprecise model parameters by adjusting the magnitude of the muscle excitations to produce the muscle forces necessary to track the experimentally measured biomechanics. Therefore, it is likely that the muscle forces and resulting contributions to the subtasks of stair ascent are minimally affected by these modeling assumptions.

Another limitation of this study is that the simulation emulates group-averaged data for subjects walking at a fixed cadence rather than a self-selected speed, and therefore, it does not capture the variability of natural stair climbing gait that is present in healthy individuals. However, a previous simulation study of healthy level walking found that relative muscle contributions were invariant with speed [29]. Therefore, we believe that the relative contributions would remain similar regardless of an individual's self-selected speed.

5 Conclusions

The purpose of this study was to identify the functional roles of individual muscles during stair ascent and the biomechanical mechanisms by which individual muscles work together to provide vertical propulsion, anteroposterior braking and propulsion mediolateral control, and leg swing. The knee extensors (VAS) and plantarflexors (SOL, GAS) were the primary contributors to vertical propulsion during the first and second halves of stance, respectively, while the hip extensors (GMAX—first half of stance, HAM—second half of stance) were the primary contributors to forward propulsion throughout stance. The hip abductors (GMEDA, GMEDP) were the primary contributors to medial control throughout stance, while the knee extensors (VAS) were the primary contributors to lateral control during the first half of stance (when they are also contributing to vertical propulsion) and the hip extensors (HAM) were the primary contributors to lateral control during the second half of stance (when they are also contributing to forward propulsion). Throughout swing, antagonistic muscles spanning the hip, knee, and ankle joints distributed power throughout the body segments to achieve a controlled and stable leg swing. By understanding the function and coordination of these muscle groups, targeted interventions and rehabilitation programs can be designed to address patient-specific deficits in stair ascent.

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