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Reconstructive

A Systematic Review of Muscle Synergies during a Walking Gait to Define Optimal Donor-Recipient Pairings for Lower Extremity Functional Reconstruction

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Background: Functional lower extremity reconstruction primarily aims to restore independent ambulation. We sought to define the synergies recruited during a walking gait to inform donor selection for various motor deficits. With these findings, we discuss the functional neuromuscular components of independent gait with the goal of informing lower extremity reconstruction.
Methods: A systematic review was performed using MEDLINE for articles published between January 2000 and December 2020. Search terms included (1) "motor module(s)," "synergy," "motor pattern," or "motor primitive" and (2) "gait," "walking," "ambulation," or "locomotion." Abstracts/full texts were reviewed by two independent reviewers.
Results: A total of 38 studies were selected. The average reported number of synergies and variance accounted for was 4.5 ± 0.9 and 88.6% ± 7.7%, respectively. Four motor modules were conserved across nearly all studies.
Conclusions: Walking can be reduced to the sequential activation of four motor modules. Activities during the stance phase are critical for both standing stability and forward progression and should be prioritized for reconstruction with the goal of preserving efficient gait. Muscles recruited during swing, except those used for ankle dorsiflexion, are less prone to injury and benefit from greater redundancy, less often necessitating reconstruction. With the emphasis on stability during stance, several synergistic or sometimes even antagonistic tendons can be used to replace their counterparts and restore efficient, independent ambulation. With a finite supply of donor tissues, and in the absence of well-defined clinical outcomes data, this research allows us to effectively prioritize reconstructive goals and maximize patient outcomes. *(Plast Reconstr Surg Glob Open 2022;10:e4438; doi: 10.1097/GOX.0000000000004438; Published online 15 August 2022.)*

INTRODUCTION

Coordinated muscle activity in the lower extremities enables efficient balance and locomotion across a variety of terrains. The multiple degrees of freedom in joint movement and muscle activity allow for a breadth of functions ranging from swimming and rock climbing to a ballerina's pointe technique. For reconstructive surgeons and their patients, however, the primary goal is to achieve functional independence, the hallmark of which is the ability to walk unassisted on a flat surface.

Walking is a cyclical pattern—the "gait cycle"—that begins when the foot strikes the ground and ends when that same foot strikes the ground again (Fig. 1). A single gait cycle, a stride, is composed of two phases: stance and swing. The stance phase is when the reference foot is in contact with the ground; the swing phase is when it is not. In 2004, Ivanenko et al[1] used electromyography (EMG) in healthy human subjects while walking, demonstrating that lower extremity muscle activity throughout a single stride can be reduced to several basic muscle activation patterns or motor modules. By reducing the activity of dozens of muscles across three joints and three dimensions into primary motor modules, the body effectively

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reduces a complex activity to a simple pattern that can be carried out unconsciously. Although the number of "modules" or "synergies" (used interchangeably) and their constituent muscles remain points of contention within the literature, the modular organization of gait has become fundamental to our understanding of walking. However, this critical concept remains underappreciated among reconstructive surgeons tasked with addressing lower extremity functional deficits affecting gait.

Technical advancements have made limb salvage a possibility for lower extremities compromised by cancer resection or trauma, but salvaged limbs can impose significant burden when functionality is not adequately restored. Advances in functional muscle/tendon transfers and the more recent emergence of lower extremity nerve transfers promise to improve patient outcomes following limb salvage. However, rigorous research defining and comparing clinical outcomes for the numerous available surgical options remains lacking. In the absence of such data to guide surgical decision-making, an understanding of the neuromuscular organization of gait can be used to glean insights into both indications and donor-recipient pairings for functional lower extremity reconstruction. To that end, we endeavored to systematically review the literature on lower extremity muscle organization during a normal walking gait. Specifically, we set out to (1) define the fundamental synergies of ambulation and (2) use these synergies to identify potential donors for various motor deficits. Finally, by combining our findings with existing knowledge on various gait pathologies, we can explore which synergies and donor-recipient pairings within them should be considered for reconstruction aimed at restoring gait.

Takeaways

Question: What are the fundamental synergies of ambulation, and can these synergies be used to identify potential donor nerves and tendons to reconstruct various motor deficits?

Findings: Walking on a flat surface can be reduced to the sequential activation of four motor modules. Synergies between the adductor compartment and quadriceps/hamstrings as well as the peroneus muscles and ankle plantar flexors present attractive donor-recipient pairing for functional reconstruction.

Meaning: Surgical plans aiming to reconstruct the functional components of independent ambulation with the suggested nerve and tendon donors identified herein could allow for the restoration and/or preservation of independent gait following significant lower extremity injury.

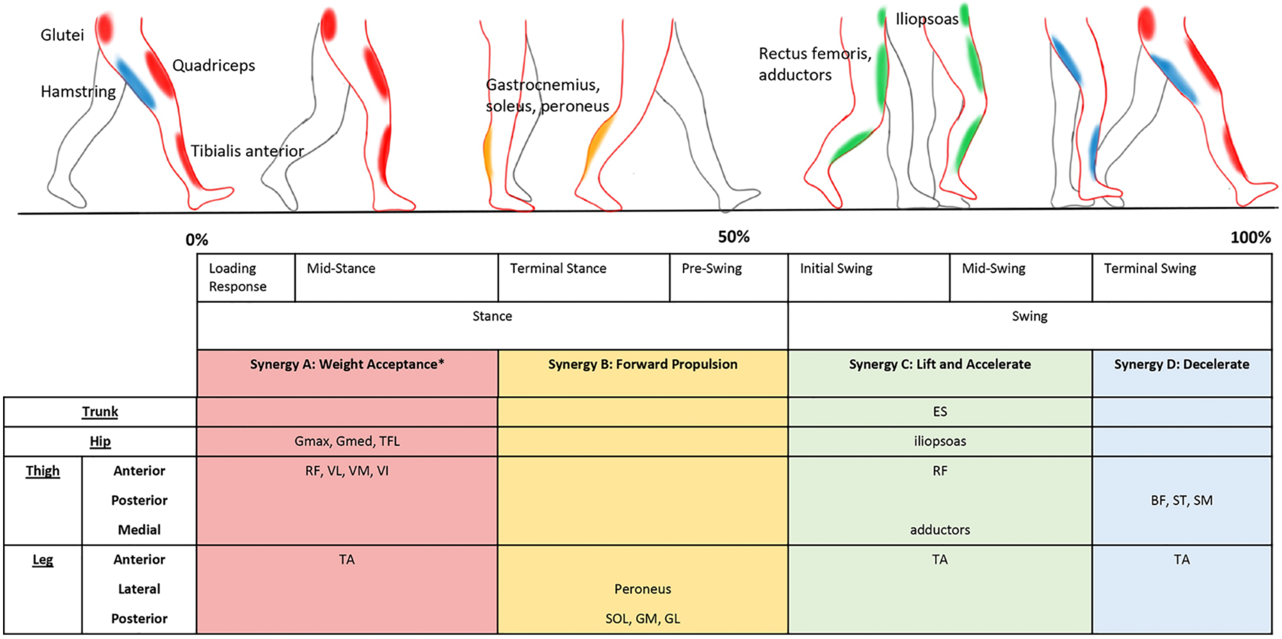
METHODS

Literature Search

A protocol was developed for a systematic literature review of primary studies with the goal of delineating the modular contraction of muscles during a walking gait. The study design as a systematic review met institutional criteria for IRB exempt research. A literature search using PubMed was used to query the MEDLINE database for all English language articles published between 2000 and 2020. Search terms, including "motor module," "synergy," "walking," and "gait," were used. An abstract was identified for each article.

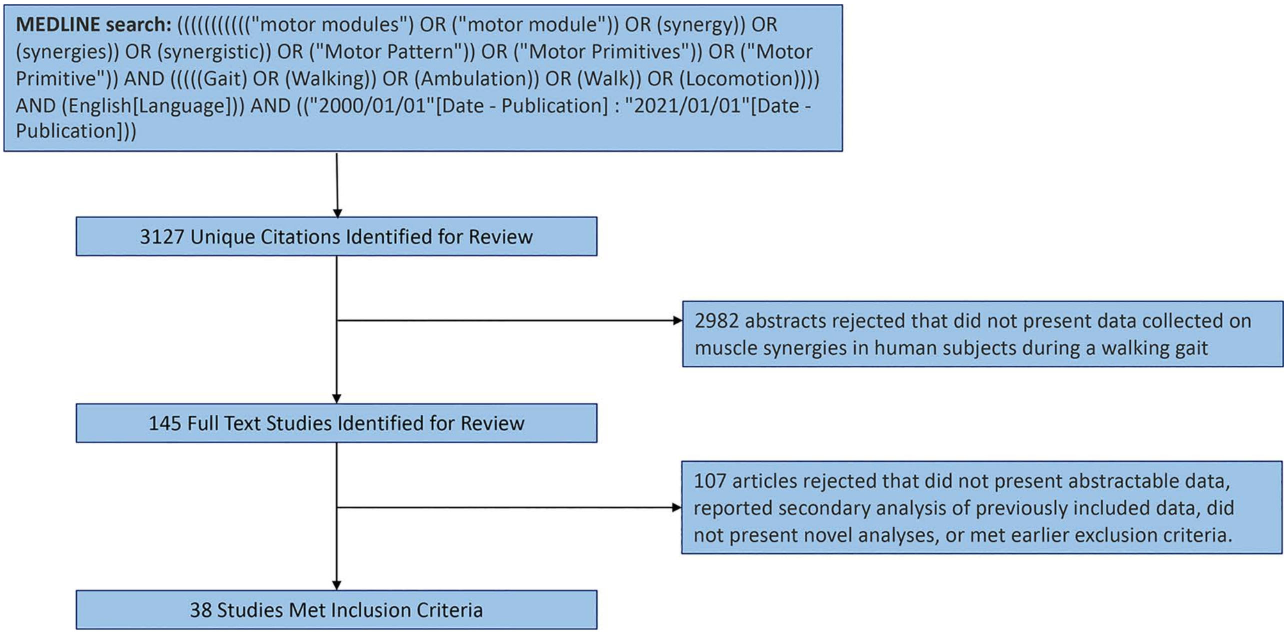
Selection Criteria

Abstracts were reviewed by two independent reviewers using selection criteria defined a priori. Abstracts were



		Loading Response Mid-Stance	Terminal Stance Pre-Swing	Initial Swing Mid-Swing	Terminal Swing
		Stance		Swing	
		Synergy A: Weight Acceptance*	**Synergy B: Forward Propulsion**	**Synergy C: Lift and Accelerate**	**Synergy D: Decelerate**
Trunk				ES	
Hip		Gmax, Gmed, TFL		iliopsoas	
Thigh	**Anterior**	RF, VL, VM, VI		RF	
	Posterior				BF, ST, SM
	Medial			adductors	
Leg	**Anterior**	TA		TA	TA
	Lateral		Peroneus		
	Posterior		SOL, GM, GL		

Fig. 1. Key phases and active muscle synergies during the gait cycle in relation to the anatomic distribution of muscle constituents. *Restoring activity of these muscles should be prioritized in reconstruction to achieve independent ambulation.



MEDLINE search: ((((((((((("motor modules") OR ("motor module")) OR (synergy)) OR (synergies)) OR (synergistic)) OR ("Motor Pattern")) OR ("Motor Primitives")) OR ("Motor Primitive")) AND (((((Gait) OR (Walking)) OR (Ambulation)) OR (Walk)) OR (Locomotion)))) AND (English[Language])) AND (("2000/01/01"[Date - Publication] : "2021/01/01"[Date - Publication]))

3127 Unique Citations Identified for Review

2982 abstracts rejected that did not present data collected on muscle synergies in human subjects during a walking gait

145 Full Text Studies Identified for Review

107 articles rejected that did not present abstractable data, reported secondary analysis of previously included data, did not present novel analyses, or met earlier exclusion criteria.

38 Studies Met Inclusion Criteria

Fig. 2. Overview of study selection process.

screened, including studies that reported muscle synergies in human subjects during a walking gait. Full-text articles were then obtained for the 145 studies that met the above criteria. These articles were reviewed, excluding any that did not present abstractable data, reported secondary analyses of data already included in the review, or were discussions, letters, or other reports without original data collection and analysis. Any disagreements on inclusion or exclusion between the reviewers were resolved by an independent third reviewer. A complete overview of the study selection process is included in Figure 2.

Data Collection

A standardized, electronic data abstraction form was created, and two independent reviewers extracted data from all selected studies. The form captured publication data, study methodologies, and results. Collected publication data included authors, institution, title, journal, and year of publication. Study methodology variables included the method for data collection, data analysis technique, number of subjects, and walking speed. Outcomes of interest included the number of synergies identified, specific muscles within each synergy, and variance accounted for (VAF)—a percentage estimating the ability of predicted motor modules to account for total EMG variability.

The data were evaluated in aggregate to determine the salient features of motor functional organization that emerged in the preponderance of studies. Since studies varied in terms of specific muscles evaluated and number of modules identified, each study's results were referenced against the gait cycle. This allowed for aggregate determination of the fewest motor modules necessary to capture the variation across studies as well as the distribution of muscles within each module. The number of modules and VAF across studies are presented as mean ± standard deviation. Secondary interests, including comparisons across walking conditions (eg, various speeds, inclination, etc.) and pathologic conditions, were also examined.

RESULTS

Study Characteristics

The search identified 3127 unique abstracts, from which 145 full-text abstracts were extracted. Thirty-eight studies met inclusion criteria (Fig. 2). Data from 416 healthy participants were included. Muscle activity was measured using surface EMG in all but two studies. Twenty-nine studies used nonnegative matrix factorization as their method for extracting muscle synergies from EMG data. Six studies used principal component analysis. One study used torque decomposition and one used factor analysis. Twenty-seven articles noted participant walking speed, ranging between 0.55 and 2.09 m/s.

Muscle Synergies

All but five studies reported the VAF of their proposed synergies. The mean VAF was 88.6% ± 7.7%. Each study identified between three and seven motor modules that compose a walking gait cycle, with an average of 4.5±0.9. Thirty-one of 38 studies (81.6%) reported either four or five synergies.

Synergies were categorized between studies using information about their temporal activation during the gait cycle and activated muscle constituents (Table 1). The synergies observed across studies could be reclassified into four temporally independent synergies, while additional synergies reported in studies with more than four synergies lacked consistent muscle composition. Synergy A was active at early stance and initial contact, providing body support during weight acceptance at approximately 5% of

Table 1. Summary of the Four Major Muscle Synergies during a Normal Walking Gait

Synergy A (5% of Gait Cycle)		Synergy B (40% of Gait Cycle)		Synergy C (80% of Gait Cycle)		Synergy D (95% of Gait Cycle)	
Muscles	Studies Reported, n (%)	Muscles	Studies Reported, n (%)	Muscles	Studies Reported, n (%)	Muscles	Studies Reported, n (%)
Vastus lateralis	24 (63.2)	Soleus	33 (86.8)	Tibialis anterior	31 (83.8)	Biceps femoris	32 (86.5)
Rectus femoris	24 (63.2)	Medial gastrocnemius	30 (78.9)	Rectus femoris	15 (40.5)	Semitendinosus	24 (64.9)
Gluteus medius	22 (57.9)	Lateral gastrocnemius	20 (52.6)	Erector spinae	12 (32.4)	Semimembranosus	9 (24.3)
VM	20 (52.6)	Peroneus	14 (36.8)	Adductor magnus/longus	10 (27.0)	Tibialis anterior	8 (21.6)
Gluteus maximus	15 (39.5)			Iliopsoas*	2 (5.41)		

*Iliopsoas was only reported by two studies for Synergy C, likely due to limitations in EMG access to this muscle.

the gait cycle. It was composed principally by vastus lateralis (reported in 63% of studies), rectus femoris (63%), gluteus medius (58%), vastus medialis (VM) (53%), and gluteus maximus (39%) (Table 1). Synergy B was active primarily at late stance and served to generate forward propulsion around 40% of the gate cycle. Active muscles included soleus (87%), medial (79%), and lateral (53%) heads of the gastrocnemius, and peroneus (37%). Synergy C was most active during the transition between stance and swing at approximately 80% of the gait cycle. Its active muscles were tibialis anterior (84%), rectus femoris (41%), erector spinae (32%), and adductors (27%). Synergy D was active during late swing and early stance, peaking around 95% of the gait cycle. Its principal muscles included biceps femoris (86%), semitendinosus (65%), and, to a lesser extent, semimembranosus (24%) and tibialis anterior (22%). These data are summarized in Table 1.

DISCUSSION

Tendon and nerve transfers have become mainstays in the management of complex neuromusculotendinous injuries of the upper extremity. With recent advancements in lower extremity limb salvage, surgeons have naturally begun to apply these same principles to restore lower extremity function. However, this field of functional lower extremity reconstruction is in its infancy, and this is the first study to systematically review the neuromuscular organization of gait and apply these findings to surgical decision-making.

Synergies of Independent Walking

Standardizing all reported synergies within the gait cycle revealed four core motor modules with relatively high VAF (Table 1), implying that the gait cycle can be fundamentally reduced into as few as four functional components as highlighted in Figure 1. During stance, coordinated muscle activation functions to stabilize the hip and knee to accept the weight of the body with heel strike (synergy A). The ankle is then stabilized while the plantar flexors work to propel the center of gravity (COG) forward (synergy B). As the leg transitions into swing, the rectus femoris, iliopsoas, and adductors flex the hip, while the tibialis anterior (TA) dorsiflexes the foot so that the toes clear the ground (synergy C). Finally, the hamstrings decelerate the forward swing of the leg while the foot remains dorsiflexed during terminal swing in preparation for the subsequent heel strike (synergy D) (Table 1).

Donor Synergy/Expendability

Functionally, lower extremity muscle activity results in forward progression, standing stability, and energy conservation during gait. These functions can be broken down into the following constituent activities: knee and hip extension (synergy A), plantar flexion (synergy B), hip flexion and dorsiflexion (synergy C), and knee flexion/hip extension (synergy D). Myriad techniques ranging from tendon and nerve transfers to free functional muscle are available to address deficits in these functions.[2–4]

Deficiencies of Knee Extension

The quadriceps are major constituents of synergy A (Fig. 1). Quadricep weakness results in a forward lean of the trunk to avoid uncontrolled knee flexion at the unstable joint.[5] In cases of quadricep deficiency, obturator to femoral nerve transfers have been described with favorable

Table 2. Potential Tendon and Nerve Donors for Functional Lower Extremity Reconstruction

Reconstructed Functions	Potential Tendon Donors*		Potential Nerve Donors*	
Knee extension reconstruction	Gracilis TFL Semitendinosus	Adductor magnus/longus† Sartorius Biceps femoris	Obturator nerve	
Knee flexion reconstruction	Adductor magnus/longus† TFL	Gracilis Rectus femoris		
Ankle dorsiflexion reconstruction	Gastrocnemius‡ FHL/FDL	Tibialis posterior	Tibial nerve‡	
Ankle plantar flexion reconstruction	Peroneus longus/brevis	EHL/EDL	Superficial fibular (peroneal) nerve	Femoral nerve

These findings are intended to guide the reconstructive surgeon who wishes to restore specific lower extremity functional deficits with minimal donor site morbidity.
EDL, extensor digitorum longus; EHL, extensor hallucis longus; FDL, flexor digitorum longus; FHL, flexor hallicus longus.
*Adequate reconstruction often requires one or more of the below nerve/tendon transfers, sometimes in combination with free functional muscle.
†Adductor longus acts secondarily as a hip extensor while the hip is flexed and a hip flexor while the hip is extended. During stance, it synergistically extends and stabilizes the hip while the quadriceps fire; and during swing, it synergistically decelerates the swinging leg with the hamstrings.
‡Tendon transfer of the gastrocnemius can be combined with nerve transfer of the tibial nerve if there is a proximal peroneal nerve.

outcomes.[6,7] The obturator nerve plays an important role in hip stabilization and, thus, fires synergistically with the quadriceps during synergy A (Table 2; Figure 1).

When nerve transfer is not possible, the use of the local tendons, including the gracilis, tensor fasciae latae (TFL), sartorius, adductor longus, and hamstrings, has also been described (Table 2).[3,8,9] Using these relatively weak and sometimes antagonistic tendons for quadriceps reconstruction may seem counterintuitive, as they would likely not fully restore muscle strength or active range of motion. However, prominent quadricep activation during synergy A suggests these muscles' role in ambulation is providing knee stability so that the forward momentum from the preceding swing can be conserved during stance. In one study of patients with anterior compartment sarcomas reconstructed with biceps femoris, semitendinosus, and/or gracilis transfer, nearly 60% of patients were able to ambulate postoperatively without the use of walking aids despite significant weakness compared with the contralateral leg.[8]

Deficiencies of Hip Stabilization

The glutei are another important muscular component of synergy A (Fig. 1). Weakness of the gluteus medius or other hip abductors innervated by the superior gluteal nerve results in a contralateral hemipelvis drop during stance phase, that is, a Trendelenburg gait.[10] Gluteus maximus tendon transfers have been described with successful outcomes for patients with gluteus medius weakness[11] likely because the glutei fire synergistically during stance in synergy A (Table 1).

Deficiencies of Plantar Flexion

Plantar flexors are the principal muscles of synergy B (Fig. 1). With diminished plantar flexor activity, walking is still possible on a flat surface, as seen in elderly patients with propulsive deficits. The biggest challenge for patients with plantar weakness becomes the ability to walk at high speeds or uphill/upstairs,[12] as the ankle cannot stabilize against natural dorsiflexion in late stance.

The peroneus muscles provide lateral ankle stability during single-leg support to maintain balance and protect against ankle sprains.[13] This synergistic contraction (Fig. 1) suggests a potential role for the peroneus longus or brevis as donor nerves or tendons to reconstruct injuries of the superficial posterior compartment, as previously described for tendon transfers for Achilles tendon rupture.[14] Similarly, the femoral nerve branches of the VM can be transferred to the nerve of the medial head of gastrocnemius to produce relatively synergistic function,[15] as quadricep activation and plantar flexion are immediately sequential actions during stance (Fig. 1; Table 2).

Except for the TA, the remaining muscles in the anterior and deep posterior compartments (toe flexors/extensors) of the leg were not identified among those necessary for a walking gait (Fig. 1) and could potentially serve as donors to provide ankle stability (Table 2).

Deficiencies of Dorsiflexion

Loss of dorsiflexion results in foot drop or steppage gait.[16] TA plays a prominent role throughout various parts of the gait cycle (Fig. 1) without any notable synergy with other below-the-knee muscles. In the absence of meaningful synergy, any expendable below-the-knee muscle could serve as a potential donor in the management of foot drop. Transfer of the tibialis posterior (TP) tendon has been described to stabilize the ankle and statically clear the toes during swing.[17] Although this is generally an improvement, the TP transfer does not restore active dorsiflexion, as the TP naturally performs an antagonistic function. Therefore, our preference is to combine a tendon transfer of the lateral head of gastrocnemius into the TA with simultaneous transfer of its nerve into the proximal peroneal nerve (Table 2).[18] The lateral head of gastrocnemius is not only expendable, leaving the medial head and soleus intact, but the ability to perform a concomitant nerve transfer when a proximal peroneal nerve is available allows the surgeon to create synergy when a synergistic donor tendon is otherwise not available.

Deficiencies of Knee Flexion and Hip Extension

The hamstring fires in synergy D, decelerating the leg during terminal swing and contributing to knee stability upon heal strike (Fig. 1). In the absence of clearly synergistic thigh musculature, expendable muscles, including the TFL, adductor compartment/gracilis, and redundant quadricep tendons, may serve as potential donors for hamstring reconstruction (Table 2). Clinically, loss of hamstring function does not seem to affect swing as much as it does stance, where weakness of the posterior thigh results in knee hyperextension shortly after heel strike.[19,20] Regarding walking on a flat surface, antagonistic quadricep tendon transfers may provide sufficient stability to allow independent ambulation.

Reconstructive Priorities to Achieve Independent Ambulation

By understanding the basic motor requirements for gait, we are also able to glean insights into potential indications for functional reconstruction. If the four synergies identified in this study make up the functional basis for independent ambulation, efforts to restore or preserve them all should allow for efficient postoperative ambulation. Although additional research is necessary to determine which muscle functions are sufficient for ambulation, by combining the results of this study with existing literature on gait pathology, we can draw conclusions that can be used as topics for future investigations.

Joint stability throughout the gait cycle, particularly during stance, is essential. Stability at each joint not only contributes to overall standing stability, but also plays an important role in forward progression by bridging the momentum generated during swing into stance. The primary progressional force during gait is the forward fall of the body, as its COG moves in front of the stance leg. The contralateral swinging leg plays an important but smaller role in accelerating the COG forward between heel strike and midstance. For the energy of the swinging leg to efficiently translate into a forward fall about the stance leg, the muscles at the hip, knee, and ankle must remain taut, accepting the weight of the more proximal unit, and ultimately the entire body, over the supporting foot. If patients must compensate for instability at any joint during this phase, the body's forward momentum is effectively disrupted, impeding forward progression and increasing energy expenditure. Although, in ideal scenarios, we strive to restore full active range of motion (ROM) in all injured muscle groups, in complex cases with multiple functions impaired and limited donor options, the restoration of joint stability without active ROM may be sufficient in restoring independent walking.

Unlike stance, muscle synergies during swing are largely focused on acceleration and subsequent declaration of the swinging leg through space. With the hip in maximal extension just before toe-off, the line of force of adductor magnus and longus lies anterior to the axis of the hip, resulting in hip flexion until 40°–70°.[21] Combined with the iliopsoas and the rectus femoris, synergy C primarily works to accelerate the hip through its swing, while the TA dorsiflexes the ankle so the toes clear the ground (Fig. 1). Although hip flexion is clearly important for ambulation, built-in redundancy with contributions from muscles innervated by both the femoral and obturator nerves may preserve function in most cases.

Knee flexion during early and midswing turns out to be largely passive. The hamstring muscles were not found to play a role in synergy C (Table 1), and flexion of the knee occurs largely passively due to gravity as the hip is flexed. The hamstring contracts concentrically only at high speeds or with walking uphill to actively generate knee flexion and hip extension.[22] The major spike in semimembranousus, semitendinosus, and biceps femoris activity occurs during synergy D when the hamstrings act as eccentric hip extensors to decelerate the swinging leg (Table 1). Their role at the knee is largely relegated to stabilization at low speeds, and patients may not require active hamstring function at the knee to walk on a flat surface independently.

LIMITATIONS

Most included articles used surface EMG to detect muscle activity and are, thus, limited by the number of leads and the ability of surface EMG to detect activity in deeper muscles. Each study also reported different average walking speeds, which could result in greater recruitment of muscles at higher speeds. The focus of this study was walking on a flat surface, and motor modules for other basic functions of daily living were not considered. Walking is just one of many lower extremity functions that may be important to patients, and our reconstructive goals must be more comprehensive to maximize patient outcomes.

CONCLUSIONS

Walking on a flat surface can be reduced to the sequential activation of four motor modules. Synergies between the adductor compartment and quadriceps/hamstrings as well as the peroneus muscles and ankle plantar flexors present attractive donor-recipient pairing for functional reconstruction. Even in the absence of obvious synergies, the built-in redundancy in lower extremity function provides a wealth of expendable donors that can help to restore ROM and stability at various joints in the lower extremity. Surgical plans aiming to reconstruct the functional components of independent ambulation with the suggested nerve and tendon donors identified herein could allow for the restoration and/or preservation of independent gait following significant lower extremity injury. Future work should review various functional lower extremity reconstruction outcomes in the context of these findings.

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