Lower Extremity Strength Is Correlated with Walking Function After Incomplete SCI

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Background: Lower extremity strength has been reported to relate to walking ability, however, the relationship between voluntary lower extremity muscle function as measured by isokinetic dynamometry and walking have not been thoroughly examined in individuals with incomplete spinal cord injury (iSCI). **Objective:** To determine the extent to which measures of maximal voluntary isometric contraction (MVIC) and rate of torque development (RTD) in the knee extensor (KE) and plantar flexor (PF) muscle groups correlate with self-selected overground walking speed and spatiotemporal characteristics of walking. **Methods:** Twenty-two subjects with chronic (>6 months) iSCI participated in a cross-sectional study. Values for MVIC and RTD in the KE and PF muscle groups were determined by isokinetic dynamometry. Walking speed and spatiotemporal characteristics of walking were measured during overground walking. **Results:** MVIC in the KE and PF muscle groups correlated significantly with walking speed. RTD was significantly correlated with walking speed in both muscle groups, the more-involved PF muscle group showing the strongest correlation with walking speed ($r = 0.728$). RTD in the KE and PF muscle groups of the more-involved limb was significantly correlated with single support time of the more-involved limb. **Conclusion:** These data demonstrate that lower extremity strength is associated with walking ability after iSCI. Correlations for the muscle groups of the move-involved side were stronger compared to the less-involved limb. In addition, PF function is highlighted as a potential limiting factor to walking speed along with the importance of RTD. **Key words:** lower extremity, muscle strength, spinal cord injuries, walking

Ambulation is a primary goal after incomplete SCI (iSCI), however, the extent to which motor function is preserved below the level of injury is widely variable, and significant impairments and limitations specifically related to walking dysfunction often persist. Although a number of mechanisms likely contribute, lower extremity muscle strength is one factor that has been reported to relate to walking ability after iSCI.¹⁻³ The strength of the knee extensor (KE) and plantar flexor (PF) muscle groups in particular are thought to play an important role in walking.

Previous studies support correlations between walking ability and gross lower extremity muscle strength (eg, lower extremity motor scores [LEMS] as measured during American Spinal Injury Association Impairment Scale [AIS] evaluation).^{2,4} Although the relationship between lower extremity strength and walking performance has been demonstrated, strength has typically

been assessed using manual muscle tests. Manual muscle testing is based on a 6-point ordinal scale that grades strength from 0 (*none*) to 5 (*seemingly normal*). These tests are subject to a ceiling effect, lack sensitivity to change, and have a relatively poor inter-rater reliability, especially at scores greater than 3.^{5,6} Accordingly, these types of tests are limited in their ability to accurately quantify strength and may limit the ability to distinguish subtle yet important differences amongst a clinical cohort such as iSCI. Further, manual muscle tests do not evaluate the temporal characteristics of muscle performance, which have been reported to be important predictors of function in other populations.⁷⁻⁹ As such, the extent to which voluntary muscle function impacts walking capacity is not adequately described.

Given the inherent limitations of manual muscle testing, more sensitive means of quantifying strength are necessary to determine whether a

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true and meaningful relationship exists and the extent to which lower extremity muscle strength and walking ability are related in persons with iSCI. Commercially available dynamometers have increased sensitivity as well as the ability to capture temporal characteristics associated with voluntary contractile efforts, making these devices attractive alternatives to manual muscle testing.¹⁰

The purpose of this study was to determine the extent to which characteristics of voluntary lower extremity muscle function (ie, maximal voluntary isometric contraction [MVIC] and rate of torque development [RTD]) in the KE and PF muscle groups correlate with self-selected overground walking speed in persons with chronic iSCI. In addition, correlations between lower extremity muscle function and spatiotemporal characteristics of walking were examined. We hypothesized that PF strength would be more highly correlated with self-selected walking speed than KE and that the temporal characteristics of muscle torque production (RTD) would improve the correlations when compared to peak torque (MVIC).

Methods

Twenty-two subjects with chronic (>6 months after injury) iSCI (C4-T10) participated in this study. Inclusion criteria were (a) age 18 to 60 years, (b) first time motor-incomplete SCI (AIS C or D), (c) upper motor neuron lesion at cervical or thoracic levels, (d) ability to walk 10 meters with maximum 1 person assist, and (e) medically stable with no history of congenital SCI or other disorders that may confound evaluation procedures. Prior to participating in the study, written informed consent was obtained from all subjects, as approved by the Institutional Review Board at the Medical University of South Carolina. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Lower extremity motor score

Upon initial evaluation, LEMS was evaluated using the AIS classification system of impairment.¹¹ The LEMS is a composite score based on bilateral

manual muscle strength tests of key muscle groups that include hip flexors, KE, ankle dorsiflexors, long toe extensors, and ankle PF. Each muscle group is scored from 0 (*total paralysis*) to 5 (*active movement, against full resistance*), thus total LEMS scores can range from 0 to 50.

Dynamometry

Bilateral strength measurements were performed in the PF and KE muscle groups of the more- and less-involved lower extremities (determined by subject self-report) using a Biodex isokinetic dynamometer (Biodex Corp., Shirley, NY). We chose to examine these muscle groups because of their antigravity responsibilities during bipedal walking and their relative importance to gait in other populations. PF strength was assessed with subjects seated in a semi-reclined position (~70° hip flexion), with the knee flexed to ~15° and the ankle in an anatomical neutral position. The axis of the dynamometer was aligned with the lateral malleolus, and the foot was secured with straps placed at the forefoot and ankle. Proximal stabilization was achieved with straps across the chest, hips, and knee. KE assessments were performed with subjects seated in the same position used for PF testing, however the knee was flexed to ~90°, and the axis of the dynamometer was aligned with the knee joint line and the leg was secured to the lever arm. For each test, participants were instructed to push against the lever arm “as hard and as fast as possible.”

MVIC was defined as the highest torque achieved during 3 maximal isometric contractions (~3 seconds contraction separated by a minimum of 60 seconds rest). Using the torque:time plots from the MVIC testing, values for the RTD were calculated in the corresponding time interval between 20% and 80% of MVIC. This time interval was chosen to minimize potential errors in the determination of the precise onset and nadir of torque development while still representing a majority of the time necessary for achieving maximal torque production. RTD was defined as the average increase in torque generated in unit time, and was calculated as previously described.¹²⁻¹⁴

Walking outcomes assessment

Subjects performed a minimum of 3 repeated walks at a comfortable self-selected speed over a 20-foot-long instrumented walkway (GAITRite CIR Systems, Sparta, NJ) that measures the geometry and the applied pressure of each footfall as a function of time. Self-selected speed, step length, and single limb support time were determined as the average of the trials for each participant and testing date.

Data analyses

All statistical analyses were performed using SPSS v16 (SPSS Inc., Chicago, IL). Torque data were analyzed using a commercially available software package (Acknowledge v3.7.1). Simple correlations were used to examine the relationship between indices of muscle strength (ie, MVIC, RTD, and LEMS) and walking variables. Level of significance was set at $\alpha = 0.05$.

Results

Twenty-two subjects completed data collection. Descriptive statistics for participant characteristics, lower extremity MVIC and RTD, and walking speed and spatiotemporal characteristics of walking are presented in **Table 1**.

Significant correlations were found between characteristics of lower extremity muscle function and walking outcomes. MVIC and RTD of both the more- and less-involved KE and PF muscle groups were significantly correlated with self-selected walking speed in persons after iSCI (**Table 2**). Of note, MVIC and RTD in both muscle groups of the more-involved limb were stronger predictors of walking speed compared to the less-involved limb. The strongest correlation with walking speed amongst the variables investigated was RTD in the more-involved PF ($r = 0.728$) (**Figure 1**). LEMS was also significantly correlated with walking speed ($r = 0.606$).

In addition, lower extremity muscle function also correlated significantly with spatiotemporal characteristics of walking. Specifically, RTD in the more-involved KE and PF muscle groups correlated with time spent in single limb support on the more involved side ($r = 0.494$ and 0.463 ,

Table 1. Participant demographics and lower extremity muscle function and walking characteristics

Patient demographics	Mean $\pm$ SD
Gender, <i>n</i>	
Female	8
Male	14
Age, years	46.2 $\pm$ 6.7
Time since injury, months	51.8 $\pm$ 22.1
Lower extremity muscle function and walking characteristics	
Knee extensor MVIC, Nm	
More-involved limb	68.91 $\pm$ 44.23
Less-involved limb	92.95 $\pm$ 52.12
Plantar flexor MVIC, Nm	
More-involved limb	31.69 $\pm$ 23.47
Less-involved limb	43.21 $\pm$ 24.78
Knee extensor RTD, Nm/s	
More-involved limb	192.22 $\pm$ 141.4
Less-involved limb	252.91 $\pm$ 192.2
Plantar flexor RTD, Nm/s	
More-involved limb	62.37 $\pm$ 67.7
Less-involved limb	104.69 $\pm$ 91.04
LEMS, /50	40.41 $\pm$ 7.82
Self-selected walking speed, m/s	0.57 $\pm$ 0.32
Step length, m	
More-involved limb	0.52 $\pm$ 0.15
Less-involved limb	0.49 $\pm$ 0.16
Percent time in more-involved single limb support	0.27 $\pm$ 0.07

Note: LEMS = lower extremity muscle strength; MVIC = maximal voluntary isometric contraction; RTD = rate of torque development.

Table 2. Relationships among lower extremity muscle functions, self-selected walking speed, and spatiotemporal walking characteristics

	SSWS	Step length _l	Step length _m	% SS _m
KE MVIC _m	.564**	.293	.315	.394
KE MVIC _l	.455*	.215	.189	.282
PF MVIC _m	.559**	.289	.298	.338
PF MVIC _l	.476*	.160	.177	.252
KE RTD _m	.658**	.419	.366	.494*
KE RTD _l	.431*	.226	.188	.317
PF RTD _m	.728**	.277	.266	.463*
PF RTD _l	.635**	.166	.212	.433
LEMS	.606**	.360	.375	.425
SSWS		.525*	.510*	.827**

Note: KE = knee extensor; LEMS = lower extremity motor score; _l = less-involved limb; _m = more involved limb; MVIC = maximal voluntary isometric contraction; PF = plantar flexor; RTD = rate of torque development; SSWS = self-selected walking speed; %SS = single limb support time.

* $P < .05$. ** $P < .001$.

Figure 1. Correlations between rate of torque development (RTD) and maximal voluntary isometric contraction (MVIC) of the more-involved muscle groups and self-selected walking speed following incomplete spinal cord injury (iSCI).

respectively) (**Table 2**). No significant correlations were found between the MVIC or RTD of the KE and PF muscle groups and step length.

Discussion

Walking places high demands on lower extremity muscles, especially about the knee and ankle joints. Biomechanical studies report that as walking speeds increase, task-specific torque and power generation increases about these joints.¹⁵⁻¹⁷ Thus, walking not only places an extremely high demand on lower extremity muscles, but these demands increase dramatically as walking speed increases.¹⁸ Following iSCI, progressive deterioration of skeletal muscle is common, and the resultant muscle is small, weak, and slow to develop force. Previous studies have demonstrated that persons with iSCI present with significant strength deficits about the knee and ankle, as well as slow walking speeds; however, the relationship between these variables is not well described.^{12,14} Data from the present study indicate that in individuals with chronic iSCI, strength of the KE and PF muscle groups are significantly correlated with walking speed as well as spatiotemporal characteristics of walking. In addition, the temporal characteristics of lower extremity muscle function (eg, RTD), especially in the weaker PF muscles, are highly correlated with walking speed, suggesting the importance of this muscle group in predicting walking function.

Although the force-generating capacity of a muscle can be reliably measured using dynamometry, it is sometimes questioned whether these measures have meaningful carry-over to task-specific performance. We suggest that the recruitment of individual muscles during functional tasks (ie, walking) and during isolated single-joint voluntary force generation (ie, dynamometric testing) involve common neural pathways, despite obvious behavioral differences. In addition, we suggest a mechanistic relationship exists between impaired muscle force generation during walking and that observed during strength testing. Our data suggest that KE and PF isometric strength could be used to predict walking speed after iSCI. This information regarding the relative contribution of skeletal muscle characteristics to walking ability may be valuable to clinical practice,

as a clear understanding of the factors that are most predictive could facilitate more appropriate and precisely defined therapeutic prescription, thereby maximizing recovery of walking during rehabilitation. The correlations between voluntary lower extremity strength and walking speed found in the present study indicate that strength about these joints is critical to walking ability following iSCI.

The significant correlations found between MVIC and self-selected walking speed generally support our a priori hypothesis that the PF muscle group would be more highly correlated with self-selected walking speed than the KE. Strength data expressed as a function of time (ie, RTD) further highlight the importance of PF function to walking speed. The relative importance of RTD versus MVIC in predicting functional performance likely reflects the dynamic role of the ankle during walking and the changing demands as function improves.

We suggest RTD to be a functionally more relevant characteristic of lower extremity muscle function. In vivo factors proposed to affect RTD include muscle fiber type,¹⁹ muscle size,²⁰ maximal muscle strength^{20,21} and neural drive to the muscle,^{20,22,23} all likely altered following iSCI. A greater RTD describes the ability to rapidly develop torque and represents the integrated slope of the torque–time curve (Δ torque/ Δ time) obtained during isometric conditions and is likely analogous to muscle power generation during nonisometric contractions. This information is not attainable using manual muscle testing, and thus its relationship to walking ability has not been thoroughly examined in this population.

Previous research has shown that RTD is significantly reduced after iSCI, with more pronounced deficits in the PF compared to the KE muscles.¹² Jayaraman et al¹⁴ reported a roughly 40% average increase in RTD in the ankle PF muscle group, with lesser gains in the KE following a locomotor training intervention. This increase resulted from improvements in both absolute strength and, more importantly, a reduced time to peak tension. The large increase in the ankle PF versus the KE muscle group with locomotor training suggests a potential hierarchy of importance in these key lower extremity muscle groups, owing to their respective roles during

walking in this population. The data in the present study provide further support for this notion. Our data suggest that a relationship between RTD and walking function exists after iSCI, with values in the more-involved PF most strongly correlated with walking speed.

The results of this study suggest that measures of isometric strength and RTD development in the PF and KE muscle groups significantly correlate with walking function following iSCI. Although we believe the findings are important and have potential implications for rehabilitation design, the inclusion criteria focused this investigation on a specific group within this clinical cohort (ie, AIS C/D, ambulatory individuals). As such, the findings should be interpreted with this in mind. Nevertheless, rehabilitation programs targeting walking function may benefit from focused intervention aimed at improving muscle function at these joints, with emphasis on the more-involved ankle PF muscle group.

Although our findings suggest that lower extremity strength plays an important role in predicting walking ability, further inspection of our data highlights a significant amount of variation in walking speed not explained by indices of strength. No doubt a number of mechanisms impact walking ability, including, but not limited to, balance, cardiovascular fitness, proprioceptive function, and walking pattern generation. As such, our intent is not to suggest that muscle strength is the only, or even most important, factor to consider when targeting walking recovery in this population. We do, however, suggest that muscle strength is important to walking (and likely other functional tasks) and should be highlighted during rehabilitation to improve locomotion. Additionally, the relative importance of the different muscle groups as well as temporal characteristics of muscle function may be more important to functional performance and its recovery. Thus, the importance of emphasizing muscle power (force $\times$ velocity) during training may provide the best opportunity for functional improvement. Future work should better define the relative importance of the various factors that contribute to walking (dys)function in this and other populations, thereby providing valuable information to rehabilitation professionals to help

guide program design. Further, as data describing the efficacy of various rehabilitative strategies continue to emerge, the potential for combination therapies that target different impairments related to walking dysfunction may be highlighted.

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Conflicts of interest: The authors declare no conflicts of interest.

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Adherence to ethics and reporting requirements: We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

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