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Gait velocity and joint power generation after stroke: contribution of strength and balance

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ABSTRACT

Objective: To assess the degree to which isometric strength of multiple lower limb muscle groups and balance is associated with gait velocity and joint power generation during gait after stroke.

Design: Sixty-three participants in a multi-site, multi-national cross-sectional, observational study underwent assessment of gait velocity (10m walk test), standing balance (computerised posturography), and isometric strength (hand-held dynamometry). Twenty-seven participants had joint power generation assessed (three-dimensional gait analysis). Bivariate associations were examined using Spearman's correlations. Regression models with partial *F*-tests were used to compare the contribution to gait between measures.

Results: While all muscle groups demonstrated significant associations with gait velocity (rho = 0.40-0.72), partial *F*-tests identified that ankle plantarflexor and hip flexor strength made the largest contribution to gait velocity. Ankle plantarflexor strength also had strong associations with habitual and fast paced ankle power generation (rho = 0.65 and 0.75). Balance had significant associations with habitual and fast gait velocity (rho = -0.57 and -0.53), with partial *F*-tests showing the contribution was independent of strength.

Conclusion: Ankle plantarflexor and hip flexor strength had the largest contribution to gait velocity. Future research may wish to refocus strength assessment and treatment to target the ankle plantarflexors and hip flexors.

Keywords: Stroke; Muscle Strength; Walking; Postural Balance.

List of abbreviations: 3D, three-dimensional; HHD, hand-held dynamometry; WBB, Wii Balance Board.

INTRODUCTION

Stroke is associated with acute and long-term impairments, such as decreased muscle strength and balance ability,[1,2] which can substantially impact the performance of daily activities. A key goal of rehabilitation following stroke is the restoration of walking at speeds that allow for community ambulation.[3] Identifying how key impairments, such as muscle strength and balance, relate to gait after stroke can aid therapists to develop targeted interventions to potentially improve gait.

Despite previous work suggesting a strong relationship between muscle strength and gait post-stroke,[4] strength training targeting the knee extensors has shown limited improvements in gait function in neurological rehabilitation.[5] While it appears that priority has been given to the knee extensors for both strength assessment and treatment,[4,5] the knee extensors have relatively minor roles in generating power for forward progression during walking.[6] Studies have shown that the primary muscle groups contributing to joint power generation during gait are the ankle plantarflexors and hip flexors;[6,7] it is possible that targeting these muscle groups may facilitate greater improvements in gait function than strengthening the knee extensors.[5]

A recent systematic review suggested that isometric strength of the ankle dorsiflexors is strongly linked with gait velocity following stroke.[4] Much previous work has examined how isometric strength relates to gait velocity after stroke, Mentiplay, et al.[4] showed varied associations between isometric strength and gait velocity for all lower limb muscle groups. Mentiplay, et al.[4] also found that the majority of studies had focused on knee extensor strength, with limited studies assessing multiple lower limb muscle groups.[4] The previous review included a range of studies irrespective of sample size and methodological quality, with the majority of included studies having relatively low sample sizes (14 out of 21 studies had less than 34 participants) and poor methodological quality (16 out of 21 studies scored less than 65%).[4] As the review suggested caution of its findings due to these limitations, the previous review[4] highlights the need for further research that examines multiple muscle groups to determine how strength relates to gait velocity, and which muscle groups have the largest contribution to gait velocity.

Reduced paretic leg propulsion is a key factor in reduced gait velocity post-stroke, with previous studies quantifying this variable using the anterior-posterior ground reaction force.[8] While the assessment of anterior-posterior ground reaction forces can provide an informative holistic measure of force production, it does not independently identify the contribution of the different muscle groups working on a joint during gait. This can be achieved by assessing joint power generation with three-dimensional (3D) gait analysis, which quantifies the product of the angular velocity and torque at each joint. Ankle joint power generation, in particular, has shown strong associations with gait velocity in neurological populations,[6] whilst increases in ankle power generation after intervention have correlated with increases in gait velocity.[9,10] Joint power generation is an important measure post-stroke; however, it requires measurement with 3D gait analysis. Previous studies have examined the associations between clinical measures of isometric strength and joint power generation in other neurological conditions,[11,12] however they have not been examined after stroke.

As current strength training interventions do not appear to improve gait function,[5] other impairments, such as balance, may impact upon gait. Previous studies have examined the relationship between balance and gait,[13-15] however these studies are often limited by the subjective rating scales used to assess balance.[13,14] Additionally, there appears to be a limited association between strength and balance following stroke,[16] and identification of which impairment, either strength or balance, contributes more to gait after stroke could potentially suggest which impairment should be targeted during rehabilitation for gait improvements.

The first aim of this study was to compare the isometric strength of various lower limb muscle groups to determine which muscle group has the largest contribution to gait velocity following stroke. The second aim was to examine whether isometric strength was related to joint power generation during gait. The third aim was to determine the relationship between balance and gait velocity, and to compare balance and strength to determine which impairment has a larger contribution to gait velocity.

METHODS

Participants

A convenience sample of post-stroke adults who were ≥21 years were recruited from hospitals in Australia and Singapore. Included participants were ≥3 months post-stroke and could walk 10m with no more than close supervision (no gait aids or orthoses, even if it was usual for them to use them for longer distances). Exclusion criteria were cerebellar stroke, cognitive issues (score below seven on the Abbreviated Mental Test Score[17]), or other medical comorbidities that would alter the outcome of physical assessments (e.g. severe arthritis). This study conforms to the STROBE guidelines (see Supplementary Checklist, Supplemental Digital Content 1, http://links.lww.com/PHM/A718).

Based on a power calculation for a correlation study with 90% power, two-tailed significance level of 0.05 and an expected average bivariate correlation of 0.40 between muscle strength and gait velocity determined from a similar study,[18] a sample size of 62 participants was required.[19]

Procedure

Procedures had approval from ethics committees at each hospital (637-14 and 2015/2562). Participants provided written informed consent prior to assessment. Gait velocity, strength and balance were assessed at each participant's hospital. A sub-group of participants, who were willing, returned for 3D gait analysis. Procedures were kept consistent between sites and the same assessor (author BFM) performed all assessments of strength, balance and gait, including marker placement for 3D gait analysis.

Gait velocity

Four trials of the 10m walk test were used to assess gait velocity; two trials each at a habitual and fast pace. Participants walked barefoot without assistive devices over a 14m walkway, with the central 10m timed using a stopwatch. Instructions were to 'walk at a comfortable pace' (habitual pace) and to 'walk as fast and as safely as possible' (fast pace). The fastest recorded gait speed for each pace was selected for analysis.

Static standing balance

A Wii Balance Board (WBB; Nintendo, Kyoto, Japan) was used to assess balance during 30s of double limb supported standing with eyes open. The WBB has been shown to be valid and reliable,[20,21] and was calibrated and filtered in accordance with previous protocols.[20] The primary balance outcome measure in this study was total path length, which sums the total distance that the centre of pressure trace moved during the trial. This is a commonly reported computerised posturography outcome measure and reflects overall body sway. Participants performed two trials, with a third recorded if the sway velocity (i.e. path length divided by the trial duration) of the two trials differed by more than 0.3cm/s. This value was chosen based on our past work in this population, as it reflects more than a 25% difference between scores. Trials were completed barefoot with no support and feet placed in a comfortable position, shoulder-width apart. Instructions to participants were to 'stand as still as possible'. The average of two (or median of three) recorded trials were selected for analysis.

Isometric strength

Lower limb isometric strength was measured using hand-held dynamometry (HHD). The device used was the Lafayette Manual Muscle Testing System Model-01165 (Lafayette Instrument Company, Lafayette IN, USA) with additional foam padding attached for comfort. Seven lower limb muscle groups were assessed: hip flexors, knee extensors and knee flexors (seated); ankle plantarflexors, ankle dorsiflexors and hip abductors (supine); and hip extensors (prone), according to a protocol described previously.[22] Participants were asked to push as hard as they could against the dynamometer. Only the paretic limb was assessed as previous work has shown low correlation between the strength of the non-paretic limb and gait velocity.[4] Two trials were recorded, and the assessor has previously demonstrated acceptable reliability.[22]

Data were filtered and resampled as per previous protocols.[22] Force data were multiplied by the lever arm (distance between the dynamometer and joint centre) to provide torque, which was subsequently normalised to body mass. Isometric strength relative to body mass was calculated as the highest reading across the two trials.

3D gait analysis

Two gait laboratories were used for 3D gait analysis. The Australian laboratory contained a 9-camera Vicon system (Vicon, Oxford, UK) sampling at 100Hz and an embedded AMTI OR6-Series force platform (AMTI, Watertown MA, USA) sampling at 1000Hz. The Singaporean laboratory contained a 10-camera Qualysis system (Qualysis, Gothenburg, Sweden) sampling at 200Hz and an embedded Kistler 9260AA6 force platform (Kistler, Winterthur, Switzerland) sampling at 1000Hz.

Participants performed gait analysis trials barefoot, without any devices and at a habitual and fast pace. The protocol aimed for five successful trials; however, fewer were accepted in cases of fatigue with repeated testing. Trials were deemed successful when there was clear foot placement of the paretic limb on the force platform, as observed by the assessor. The marker set was a cluster-based lower limb model similar to previous research.[23] Raw marker data were labelled using Vicon Nexus and Qualysis Track Manager software at the Australian and Singaporean laboratories, respectively. Data from both laboratories were then imported to Visual3D (C-motion, Inc., Germantown MD, USA), with the same 3D model used for data from both sites. Marker trajectory and force plate data were filtered using a 10Hz lowpass 4th order Butterworth filter prior to calculation of joint power generation.

A standard inverse dynamics approach was used to calculate net joint moments, with the moments multiplied by joint angular velocity to calculate net joint power generation during the gait cycle. Joint power was then normalised to body mass. Normalised power generation was filtered with a zero-phase shift 15Hz lowpass 4th order Butterworth filter. Primary outcomes were peak sagittal plane power that corresponded to the ankle plantarflexors (A2), knee extensors (K2), hip extensors (H1) and hip flexors (H3).[6] Outcomes corresponding to other muscle groups (e.g. ankle dorsiflexors or knee flexors) were not included as these absorb, not generate, power during gait. The median of successful trials was used for analysis.

Statistical analysis

Descriptive statistics were used for participant characteristics and gait, strength and balance measures. The assumption of normality for some characteristics (body mass and time since stroke) and measures (strength of the ankle plantarflexors, hip abductors and hip extensors, total path length, habitual and fast knee and hip extensor power) was not met. To provide a consistent analysis when examining differences between the Australian and Singaporean cohorts, Mann-Whitney U tests (continuous variables) and Chi-Squared tests (categorical variables) were performed. Spearman correlations were used to examine bivariate associations between measures.

Separate multivariable linear regression models were used to analyse the contribution of strength and balance to gait measures. All models were adjusted for confounders of age, gender, time since stroke (log transformed) and country of recruitment (to control for discrepancies in 3D equipment and participant nationalities), with body mass adjusted within strength and power generation. The regression models were first created with a base model of covariates, with either gait velocity or joint power generation as the dependent variable. One independent variable was then entered (strength or balance) and the process was then repeated for the other variables. The change statistics were examined to determine the incremental value of each measure over the covariates.

Regression models with partial *F*-tests were used to statistically compare the strength of each muscle group in their contribution to gait.[24] The muscle groups that demonstrated the largest associations between strength and gait were compared. A total regression model was created with the base model of covariates and two 'competing' muscle groups. One muscle group was then removed from the model to determine the individual effect of that muscle group on the total model, with this repeated to examine both muscle groups. If both muscle groups had significant *P*-values or both had non-significant *P*-values, then no statistical difference existed between them. The partial *F*-test was also used to compare strength and balance in their contribution to gait velocity.

The regression residuals were examined to determine if they adequately met the assumptions for least squares regressions. Significance was set at $P<0.05$ for analyses, with Spearman values interpreted as very strong (≥0.80), strong (0.60-0.79), moderate (0.40-0.59), weak (0.20-0.39), or very weak (<0.20).[25] Given the hypothesis-generating and exploratory nature of the current study, the results were not adjusted for multiplicity. Analyses were performed with the Statistical Package for Social Sciences version 23 (IBM Corp., Armonk NY, USA).

RESULTS

Participants

Sixty-three participants were recruited (Table 1) and a sub-group of 27 (13 from Australia and 14 from Singapore) returned for 3D gait assessment. Significant differences between the Australian and Singaporean cohorts were found for type of stroke (potentially due to the typical patient cohort at each hospital), as well as ankle plantarflexor and hip extensor power generation.

Bivariate associations

Table 2 provides the Spearman correlations among measures. All muscle groups were found to have moderate to strong correlations between measures of strength and gait velocity (rho = 0.40-0.72). Ankle plantarflexor strength had strong significant associations with habitual and fast ankle power generation (rho = 0.65 and 0.75). Knee extensor and hip extensor and flexor strength had very weak to moderate correlations with their corresponding power generation measures (rho = 0.07-0.44). The association between balance and habitual and fast gait velocity had significant moderate correlations (rho = -0.57 and -0.53).

The Spearman correlations between muscle strength and balance revealed weak associations (rho ≤ -0.35). Strong to very strong associations were found between habitual and fast gait velocity and joint power generation at the ankle (rho = 0.84 and 0.66 respectively for habitual and fast gait), hip flexors (rho = 0.86 and 0.88), and hip extensors (rho = 0.81 and 0.81), whilst weak to moderate for knee extensor power generation (rho = 0.46 and 0.30).

Multivariable contributions to gait

The results of the regression analyses are shown in Table 3. All regression models adequately met the assumptions for least squares regressions. Examination of the *P*-value change revealed that the strength of all muscle groups had significant incremental value over the base model of covariates for their contribution to gait velocity (*P*'s<0.01). The strength of the hip flexors, ankle plantarflexors, knee flexors and ankle dorsiflexors demonstrated the largest R^2 increment over the base model. Further analysis was required to determine which muscle group made the largest contribution to gait velocity.

Significant incremental increases over the covariates were shown for the contribution of ankle plantarflexor strength to ankle power generation (*P*'s≤0.01). In contrast, knee and hip strength did not demonstrate significant increments over the covariates for knee and hip power generation (*P*'s>0.05). No further analysis was required as the ankle plantarflexors were the only muscle group to demonstrate a significant contribution to joint power generation.

Balance had significant incremental value over the covariates for the contribution to gait velocity (P's≤0.01). The incremental R^2 values were lower than those for strength, although further analysis was required to statistically compare strength and balance.

Comparison of lower limb muscle groups

The muscle groups with the largest multivariable R^2 increments were compared in their contribution to gait velocity (ankle dorsiflexors, ankle plantarflexors, hip flexors and knee flexors) using partial F-tests (Table 4). Ankle dorsiflexor and knee flexor strength did not provide significant additional value over the other muscle groups in the contribution to gait velocity at either pace. The partial F-test showed that ankle plantarflexor and hip flexor strength provided significant additional value over the other muscle groups, with both having significant value over each other.

Strength compared to static standing balance

Table 5 presents the results of partial F-tests comparing ankle plantarflexor and hip flexor strength with balance in the contribution to gait velocity. The magnitude of contribution was higher for strength (indicated by larger R^2 reductions), however balance still had a significant contribution to gait velocity independent of strength (indicated by significant P-value when removing balance). The final step combined all three measures in the same model which demonstrated that all measures made a significant contribution to gait velocity independent of other measures.

DISCUSSION

This study involved an assessment of the relationships between muscle strength and balance with gait velocity and joint power generation in a multi-national setting. Overall the results were that: 1) the strength of the ankle plantarflexors and hip flexors made the largest contribution to gait velocity following stroke when compared to the strength of other lower limb muscle groups; 2) isometric ankle plantarflexor strength has a significant association with ankle power generation during gait; and 3) balance had a significant contribution to gait velocity that was independent of muscle strength.

The current study showed higher correlations between isometric strength and gait velocity across all muscle groups compared to a similar previous study.[18] Our study builds on previous research and, as suggested by the previous review by Mentiplay, et al.[4] examined multiple lower limb muscle groups together. Our results suggested that the ankle plantarflexors and hip flexors had the largest contribution to gait velocity, with these two muscle groups also providing two of the major power generation events for forward propulsion during gait.[6,7] Both the ankle plantarflexors and hip flexors act during the push off phase of gait to propel the limb forward. Previous studies have shown the importance of ankle plantarflexor and hip flexor power generation for stroke rehabilitation.[6,9,10] The results from the current study complement previous research that has suggested focus should be shifted towards training these muscle groups to potentially see improved gait outcomes in neurological rehabilitation.[5,26]

The current study found similar results to the previous systematic review by Mentiplay, et al.[4] which showed that isometric strength of the knee extensors demonstrated moderate associations with gait velocity. This may help to explain why the majority of strength training interventions, which tend to focus on the knee joint, have not resulted in significant improvement in gait function.[5] It should be noted that knee extensor strength may be important for other functional tasks, such as stair climbing,[27] and a sufficient amount of knee extensor strength is required to support the body to stand.[28] However, the role of the knee extensors may be less important once walking is achieved. While the knee extensors do contribute to gait, the joint power generation at the knee is much lower than at the ankle and hip. This may be the reason for the results in the current study; with our results supported by previous work[4] that has shown lower correlations between knee extensor strength and gait velocity compared with ankle or hip muscle groups. Consequently, for rehabilitation programs focused on improving gait velocity, an emphasis may need to be placed on also prioritising strengthening of the ankle and hip for optimal outcomes.

The current study demonstrated slightly stronger associations between ankle plantarflexor strength and ankle power generation in comparison with previous studies in cerebral palsy and traumatic brain injury.[11,12] These strong associations are interesting as isometric strength is assessed under static conditions and power generation under dynamic conditions. Assessment of isometric strength is warranted as stronger isometric force could potentially optimise the elastic recoil of the Achilles tendon during gait.[29] However, other assessments that replicate or mimic the Achilles tendon recoil, such as plyometrics or ballistic exercise,[26] may have stronger associations with gait function after stroke.

Balance had a significant contribution to gait velocity, with similar results seen in previous studies following stroke.[13-15] We also found weak correlations between muscle strength and balance (rho $\leq$ -0.35) similar to previous work,[16] despite both measures making significant contributions to gait velocity. Previous research in people with knee osteoarthritis has shown similar results that strength and balance have differing yet significant contributions to gait velocity,[30] suggesting that strength and balance may not be associated with each other, however both significantly contribute to gait velocity in clinical populations. Therefore, assessment and treatment of balance may be warranted in clinical practice to improve gait velocity after stroke. Although the current study showed that the contribution of muscle strength to gait had larger magnitudes than balance, balance was significantly and independently related to gait velocity.

Clinical Implications

Assessment and treatment of knee extensor strength appears to have been prioritised in previous research,[4,5] however there is limited evidence that strengthening this muscle group translates to improved gait outcomes.[5] Our findings suggest that the focus of strength assessment and treatment should also include the main contributors to gait velocity, the ankle plantarflexors and hip flexors. As the optimisation of gait velocity is a major goal following stroke,[3] it may be beneficial to treat the ankle plantarflexors and hip flexors during rehabilitation; however, future research is needed to confirm these suggestions through intervention-based research. Additionally, the specificity of training methods for treating walking impairments (e.g. the speed and range of movement)[5] may also need to be considered.

Study Limitations

It is acknowledged that correlations do not indicate causation and therefore improvements in strength or balance may not translate to improvements in gait. Nonetheless, the results from this study can be used to guide future studies and interventions aimed at facilitating the improvement of gait velocity.

This study is similar to previous work[18] that has examined the associations between isometric strength and gait velocity post-stroke. However, by including measures of balance and joint power generation, this international and multi-site project makes a unique contribution to the literature via its wide-ranging assessment of the associations between strength, balance, gait velocity and joint power generation.

The standardised HHD protocol used for strength assessment[22] does not optimally resemble the joint positions or dynamic muscle contractions required during gait. Future research could examine the strength of lower limb muscles in positions that are more typical of gait or assess dynamic and ballistic measures of muscle power.

The current study did not normalise gait velocity to body size. There was a very weak correlation between gait velocity and height (Spearman = -0.14 and -0.08 for habitual and fast gait velocity), and normalisation of gait velocity did not alter the results of the study. We decided to report non-normalised gait velocity to enhance the clinical interpretation of our results.

The varying number of successful trials for 3D gait analysis (range of one to five) may be a limitation. We intended to perform five successful trials per person, however this was not always possible due to participant fatigue either reported by the subject or observed by the examiner. A compromise for some participants was made between a sufficient amount of trials to be representative of their usual gait pattern and concerns of the increasing variability that occurs when fatigued. Visual examination of the association between strength and power generation for those with less than three successful trials compared to those with three or more successful trials showed no observable differences. The use of two gait laboratories may also be a limitation; although the current study used the same assessor to maximise marker placement reliability. We also had a large range in the time since stroke of participants, which may have affected the results. As such, all regression analyses included the country of recruitment and time since stroke as covariates.

Participants included in this study were a convenience sample and the selection criteria may have resulted in participants who had higher levels of ability post-stroke, which may not be representative of the entire stroke population. Additionally, all participants were asked if they were willing to undergo 3D gait analysis and only 27 participants returned. It is possible that the regression models that examined joint power generation may have been underpowered due to these lower participant numbers for the 3D gait analysis, which could limit the findings of this study. It is also acknowledged that other impairments that were not measured in this study (e.g. spasticity) may influence gait after stroke and that other measures of gait function may be equally as important as velocity and power generation.

CONCLUSIONS

Isometric strength of the ankle plantarflexors and hip flexors made the largest contribution to gait velocity across lower limb muscle groups. Measurements of ankle plantarflexor strength also had moderate to strong associations with ankle power generation. Balance is another measure that showed a significant contribution to gait velocity independent of muscle strength. Future work should examine how increased ankle plantarflexor and hip flexor strength impacts upon gait following stroke.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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LIST OF TABLES

Table 1. Participant characteristics.

	Total (n = 63)	**Location 1 (n = 22)**	**Location 2 (n = 41)**	**Difference between cohorts (*P*-value)**
Gender, male *n*	34	10	24	0.32
Age (years)	60 ± 13	60 ± 16	59 ± 11	0.68
Height (cm)	164 ± 10	167 ± 9	162 ± 10	0.16
Mass (kg)	67 ± 14	72 ± 18	64 ± 11	0.16
Time since stroke (months)	39 ± 51	57 ± 69	30 ± 35	0.15
Stroke paretic side, left *n*	33	11	22	0.78
Type of stroke				**0.04***
Haemorrhage, *n*	16	9	7	
Infarct, *n*	46	12	34	
Both, *n*	1	1	0	
Assistive devices used outdoors				0.97
No, *n*	37	13	24	
Yes, *n*	26	9	17	
Gait velocity (m/s)				
Habitual pace	0.85 ± 0.37	0.74 ± 0.31	0.91 ± 0.38	0.05
Fast pace	1.07 ± 0.47	0.92 ± 0.42	1.15 ± 0.48	0.06
Static standing balance (cm)				
Total path length	38.4 ± 30.9	47.9 ± 47.7	33.2 ± 14.3	0.83
Isometric strength (Nm/kg)				
Ankle dorsiflexors	0.13 ± 0.09	0.10 ± 0.09	0.15 ± 0.09	0.06
Ankle plantarflexors	0.22 ± 0.12	0.18 ± 0.10	0.24 ± 0.13	0.12
Hip abductors	0.75 ± 0.35	0.82 ± 0.37	0.71 ± 0.34	0.12
Hip extensors[#]	0.83 ± 0.38	0.99 ± 0.45	0.75 ± 0.31	0.05
Hip flexors	0.59 ± 0.24	0.63 ± 0.22	0.57 ± 0.25	0.33
Knee extensors	1.00 ± 0.34	0.93 ± 0.35	1.04 ± 0.34	0.25
Knee flexors	0.49 ± 0.28	0.44 ± 0.29	0.52 ± 0.27	0.23
Habitual power generation (W/kg)				
A2 (ankle plantarflexors)	1.42 ± 0.81	1.06 ± 0.72	1.75 ± 0.77	**0.04***
K2 (knee extensors)	0.69 ± 0.43	0.77 ± 0.57	0.62 ± 0.25	0.92
H1 (hip extensors)	1.37 ± 1.32	0.61 ± 0.64	2.07 ± 1.41	**<0.01***
H3 (hip flexors)	0.97 ± 0.66	0.70 ± 0.41	1.22 ± 0.76	0.07
Fast power generation (W/kg)[†]				
A2 (ankle plantarflexors)	1.89 ± 0.98	1.42 ± 0.99	2.50 ± 0.56	**<0.01***
K2 (knee extensors)	1.08 ± 0.63	1.20 ± 0.79	0.93 ± 0.31	0.62
H1 (hip extensors)	2.07 ± 1.91	0.87 ± 0.81	3.63 ± 1.80	**<0.01***
H3 (hip flexors)	1.44 ± 0.84	1.22 ± 0.98	1.72 ± 0.52	0.05

Note: Continuous variables reported as mean ± standard deviation. Differences between the cohorts assessed with Mann-Whitney U tests for continuous variables and Chi-Squared tests for categorical variables. ***** = significant difference between Location 1 and Location 2 cohorts; [#] = hip extensors only measured in 50/63 participants (17/22 from Location 1; 33/41 from Location 2); [†] = fast pace joint power only measured in 23/27 participants (13/13 from Location 1; 10/14 from Location 2). Successful trials recorded during 3D gait analysis ranged from one to five for both habitual and fast pace (27 participants for habitual = 1 had 1 trial, 5 had 2 trials, 14 had 3 trials, 5 had 4 trials and 2 had 5 trials; 23 participants for fast = 2 had 1 trial, 3 had 2 trials, 15 had 3 trials, 1 had 4 trials, 2 had 5 trials).

Table 2. Bivariate associations among isometric strength, balance, gait velocity and joint power generation.

	Habitual gait velocity (n = 63)	**Fast gait velocity (n = 63)**	**Habitual power (n = 27)**	**Fast power (n = 23)**
Isometric strength				
Ankle dorsiflexors	**0.62^**	**0.64^**	--	--
Ankle plantarflexors	**0.63^**	**0.67^**	**0.65^**	**0.75^**
Hip abductors	**0.49**	**0.52**	--	--
Hip extensors#	**0.40**	**0.43**	0.29	0.28
Hip flexors	**0.53**	**0.56**	**0.42**	**0.44**
Knee extensors	**0.51**	**0.54**	**0.42**	0.07
Knee flexors	**0.68^**	**0.72^**	--	--
Static standing balance				
Total path length	**-0.57**	**-0.53**	--	--

Note: all values are Spearman's correlations, with significant correlations in bold ($P < 0.05$). Power generation and isometric strength correlations performed between corresponding muscle groups only (e.g. ankle plantarflexor strength and ankle power generation). ^ = strong correlation according to the thresholds of Evans (1996)[25]; # = assessment of hip extensors performed in 50/63 participants for habitual and fast gait velocity, 23/27 for habitual power generation, and 20/23 for fast power generation. Habitual and fast power refers to the gait speed during assessment of joint power generation during gait.

Table 3. Regression results for the contribution of isometric strength and balance to gait velocity and joint power generation.

	Base model R^2	R^2 increment	P-value of increment	Total R^2	Base model R^2	R^2 increment	P-value of increment	Total R^2
	Habitual gait velocity (n = 63)				**Fast gait velocity (n = 63)**			
Strength (Nm/kg)								
Ankle dorsiflexors	0.201	0.252	< **0.01***	0.453	0.157	0.299	< **0.01***	0.457
Ankle plantarflexors	0.201	0.291	< **0.01***	0.491	0.157	0.346	< **0.01***	0.503
Hip abductors	0.201	0.211	< **0.01***	0.412	0.157	0.263	< **0.01***	0.420
Hip extensors#	0.281	0.133	< **0.01***	0.414	0.211	0.146	< **0.01***	0.357
Hip flexors	0.201	0.299	< **0.01***	0.500	0.157	0.342	< **0.01***	0.499
Knee extensors	0.201	0.138	< **0.01***	0.339	0.157	0.173	< **0.01***	0.330
Knee flexors	0.201	0.274	< **0.01***	0.475	0.157	0.337	< **0.01***	0.494
Balance (cm)								
Total path length	0.201	0.103	< **0.01***	0.303	0.157	0.089	**0.01***	0.246
	Habitual power (n = 27)†				**Fast power (n = 23)†**			
Strength (Nm/kg)								
Ankle plantarflexors	0.408	0.206	< **0.01***	0.614	0.469	0.167	**0.01***	0.636
Knee extensors	0.091	0.097	0.13	0.189	0.080	0.025	0.50	0.105
Hip extensors#	0.562	0.007	0.61	0.569	0.607	0.007	0.62	0.615
Hip flexors	0.442	0.058	0.13	0.500	0.106	0.172	0.06	0.278

Note: results from linear regression models, with analyses adjusted for age, gender, time since stroke (log transformed) and country recruited (body mass adjusted for within strength and joint power generation scores). R^2 increment is the change in R^2 of each variable over a base model of covariates. The P-value of increment is the significance level of the R^2 increment. Total R^2 is the total combined model with covariates (base model R^2) and the independent variable (R^2 increment). Bold P-values with ***** indicates significant increment. # = hip extensor models only include data from 50/63 participants for gait velocity, 23/27 for habitual power generation, and 20/23 for fast power generation; † = regression models for joint power generation had different dependent variables between models (corresponding muscles have been used for joint power and strength), hence the differing base model R^2 values (knee power generation had very low R^2 values for the covariates and knee extensor strength, adding to previous research that has shown limited knee power generation during gait).

Table 4. Comparison between the isometric strength of lower limb muscle groups for their contribution to gait velocity.

	Total R^2	Reduction in R^2	*P*-value#	Total R^2	Reduction in R^2	*P*-value#
	Habitual gait velocity (n = 63)			**Fast gait velocity (n = 63)**		
ADF vs APF	0.504			0.518		
Remove APF		0.051	**0.02***		0.061	**0.01***
Remove ADF		0.013	0.23		0.015	0.19
ADF vs HF	0.526			0.535		
Remove HF		0.073	**0.01***		0.078	**< 0.01***
Remove ADF		0.026	0.08		0.036	**0.04***
ADF vs KF	0.492			0.511		
Remove KF		0.039	**0.04***		0.054	**0.02***
Remove ADF		0.017	0.17		0.017	0.17
ADF did not provide significant additional value over APF, HF and HF for 5/6 partial *F*-tests						
KF vs APF	0.521			0.544		
Remove APF		0.046	**0.02***		0.050	**0.02***
Remove KF		0.030	0.07		0.041	**0.03***
KF vs HF	0.518			0.532		
Remove HF		0.043	**0.03***		0.038	**0.04***
Remove KF		0.018	0.15		0.033	0.05
KF did not provide significant additional value over APF and HF for 3/4 partial *F*-tests						
APF vs HF	0.542			0.556		
Remove HF		0.051	**0.02***		0.053	**0.01***
Remove APF		0.042	**0.03***		0.057	**0.01***
APF and HF demonstrate significant additional value over each other, no statistical difference observed between the two muscle groups						

Note: Total R^2 column reflects the total model containing the covariates (age, gender, time since stroke and country recruited) and measures of strength for both muscle groups. **#** = *P*-value is from a partial *F*-test evaluating the value of one muscle group over the other and vice versa. For example, the first test comparing ADF and APF strength for habitual gait velocity indicates APF strength to provide value over ADF strength as shown by the significant *P*-value when APF strength is removed from the total model (0.02) and the non-significant *P*-value when ADF strength is removed from the total model (0.23). Bold *P*-values with ***** indicates significance. ADF = ankle dorsiflexors; APF = ankle plantarflexors; HF = hip flexors; KF = knee flexors.

Table 5. Comparison between isometric strength and balance for their contribution to gait velocity.

	Total R^2	**Reduction in R^2**	***P*-value#**	**Total R^2**	**Reduction in R^2**	***P*-value#**
	Habitual gait velocity (n = 63)			**Fast gait velocity (n = 63)**		
Balance vs APF	0.550			0.548		
Remove APF		0.247	**< 0.01***		0.302	**< 0.01***
Remove Balance		0.059	**0.01***		0.045	**0.02***
Balance vs HF	0.550			0.537		
Remove HF		0.247	**< 0.01***		0.291	**< 0.01***
Remove Balance		0.050	**0.02***		0.038	**0.04***
Balance vs APF and HF	0.590			0.591		
Remove HF		0.040	**0.02***		0.043	**0.02***
Remove APF		0.040	**0.02***		0.054	**0.01***
Remove Balance		0.048	**0.01***		0.035	**0.03***

Note: Total R^2 column reflects the total model containing the covariates (age, gender, time since stroke and country recruited) and measures of strength and balance. # = *P*-value is from a partial *F*-test evaluating the value of one measure over the other and vice versa. For example, the first test comparing balance and APF strength for habitual gait velocity indicates both measures to provide independent value to the model as shown by the significant *P*-value when APF strength is removed from the total model (<0.01) and the significant *P*-value when balance is removed from the total model (0.01). Bold *P*-values with * indicates significance. APF = ankle plantarflexors; HF = hip flexors.