Journal of Biomechanics 96 (2019) 109345

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Decreased rate of leg extensor force development in independently ambulant patients with acute stroke with mild paresis

Ryota Shimose [a,b,*], Shinobu Shimizu [c], Aya Onodera [d], Kazuhiko Shibata [b,e], Yuta Ichinosawa [f], Ikumi Enoki [g], Satoshi Tsunoda [b], Hajime Miura [h], Hiroyuki Watanabe [c], Atsuhiko Matsunaga [b,c]

[a] Department of Physical Therapy, Health Science University, Yamanashi, Japan
[b] Graduate School of Medical Sciences, Kitasato University, Kanagawa, Japan
[c] School of Allied Health Science, Kitasato University, Kanagawa, Japan
[d] Department of Rehabilitation, Kitasato University East Hospital, Kanagawa, Japan
[e] Department of Rehabilitation, Sagamihara Chuo Hospital, Kanagawa, Japan
[f] Department of Rehabilitation, Kitasato University Medical Center, Saitama, Japan
[g] Department of Rehabilitation, Mitsui Memorial Hospital, Tokyo, Japan
[h] Funabashi Municipal Rehabilitation Hospital, Chiba, Japan

ARTICLE INFO

Article history:
Accepted 14 September 2019

Keywords:
Stroke
Rate of force development
Lower extremity
Acute stroke

ABSTRACT

We aimed to examine the rate of force development (RFD) of knee extensors on both sides in independently ambulant patients with acute stroke with mild paresis compared with that in age-matched healthy adults. A total 31 patients with acute stroke history (patient group: 67 ± 12 years) and 54 age-matched healthy, community-dwelling adults (control group: 67 ± 8 years) were included. Maximum voluntary contraction (MVC) and RFD were assessed <1 month post-stroke during isometric knee extension (sitting position; 90° knee flexion) using a hand-held dynamometer. RFD was measured as the average slope of the torque–time curve over time intervals of 0–50 ms and 0–200 ms from contraction onset. In the patient group, MVC and RFD for 0–50 ms were significantly lower on the affected side than on the unaffected side ($p < 0.01$). RFD was significantly decreased in the patient group, to 32%–38% and 62%–71% of that in the control group, over 0–50 ms and 0–200 ms, respectively, regardless of the affected side ($p < 0.01$). No significant differences in MVC between patient and control groups were observed for either side. RFD of the knee extensors significantly decreased without MVC reduction in patients with acute stroke history compared with that in age-matched healthy adults in both the affected and unaffected sides. These results suggest that decrease in RFD was initiated from the acute phase of stroke, even in patients with stroke who had good motor function.

1. Introduction

Isometric strength is measured as the highest force value someone can produce during maximum voluntary contraction (MVC) strength. However, recently, the rate of force development (RFD), defined as the change in force divided by the change in time from the onset of contraction, has been recommended for the assessment of muscle contractility because RFD is strongly related to functional daily tasks that require rapid action (e.g., walking) and more sensitive to detect acute and chronic changes in neuromuscular function compared with that in MVC alone (Maffiuletti et al., 2016).

Although numerous studies have reported RFD in healthy adults, RFD in stroke patients has rarely been studied. Moreover, previous studies have limited their investigations of RFD to chronic stroke patients. For example, in chronic stroke patients who can walk independently, RFD is lower in the paretic limb than in the non-paretic limb in quadriceps (Horstman et al., 2010) and plantar flexors (Fimland et al., 2011). In addition, RFD of the non-paretic limb decreased in patients with chronic stroke compared with that in healthy adults (Horstman et al., 2010). Bilateral RFD influences walking speed in chronic stroke patients (Mentiplay et al., 2018; Pohl et al., 2002; Takeda et al., 2018). Although RFD is a sensitive parameter to detect the changes in neuromuscular function compared with MVC alone (Maffiuletti et al., 2016), RFD of both sides

* Corresponding author at: 7187 Kodachi, Fujikawaguchiko-cho, Minamitsuru-gun, Yamanashi 401-0380, Japan.
E-mail address: ryota.shimose.17@gmail.com (R. Shimose).

https://doi.org/10.1016/j.jbiomech.2019.109345
0021-9290/

in patients with acute stroke is unclear and the nature of stroke in RFD remains to be elucidated. A better understanding on the role of RFD in rehabilitation is important for improving daily activities, such as walking. To this end, the present study aimed to examine RFD of the knee extensors on both sides in independently ambulant patients with history of acute stroke compared with that in age-matched healthy adults.

2. Methods

2.1. Participants

This study was approved by the Ethics Committee at Kitasato University School of Allied Health Sciences (No. 2014-017). We recruited consecutive patients with history of acute stroke with no or slight paresis without pathological associated movement in order to measure muscle strength. The assessment of functional performance level (i.e., ability to walk without any assistance in the ward) showed that all patients had no disability or slight disability. All patients were admitted to the Sagamihara Chuo Hospital and Kitasato University East Hospital from June 2015 to June 2017. The exclusion criteria for this study were a history of cerebrovascular, cardiovascular, or neuromuscular disease prior to stroke onset or other conditions that limited walking (e.g., dementia, low vision, higher brain dysfunction). Patients were also excluded if MVC and RFD of the lower extremities could not be measured within 1 month post-stroke because of intensive treatment or physical deconditioning. Consequently, 31 patients with history of acute stroke were included in this study.

Age-matched healthy, community-dwelling adults who were registered at a temporary employment agency in Kanagawa, Japan, were subjected to the same exclusion criteria as the patient group. All of the healthy adults included in the study were able to walk without any assistance or aid and were therefore recruited as controls. Those who have regularly performed vigorous and sport-like exercises were excluded. Ultimately, 54 healthy adults were included in the control group.

2.2. Participant characteristics

Age, sex, and body weight were recorded for all participants. Information on stroke type (hemorrhage or infarction), side of hemiparesis, severity of lower-extremity paresis (Brunnstrom recovery stages: BRS), and maximum walking velocity were recorded for all patients. BRS include flexor and extensor synergies, synergistic movements, and movements out of synergy. Maximum walking velocity was defined as the patient's fastest possible walking velocity without running.

2.3. MVC and RFD during knee extension

MVC and RFD during isometric knee extension were assessed using a handheld dynamometer (μTas F1, ANIMA, 3-65-1, Shimoishiwara, Chofu, Tokyo, Japan) in both groups. The assessment of isometric rate of torque development using a handheld dynamometry is reliable following stroke (Mentiplay et al., 2018). In the patient group, assessment was performed within one month of stroke onset. Participants were asked to sit on a platform with the hip and knee flexed at an angle of 90° and to push against the dynamometer pad (placed 3 cm above and in front of the malleoli) by attempting to straighten the knee as fast and forcefully as possible, with the patient's arms crossed across his or her chest, three times on each side. The dynamometer signal was sampled at a 1000 Hz analog-to-digital conversion rate using an analog-to-digital converter. The signal was also converted to torque and smoothed by a digital filter using a cutoff frequency of 15 Hz (Aagaard et al., 2002). The highest torque for a given trial on each side was used as MVC. RFD was calculated as the average slope across three trials of the torque-time curve (Δtorque/Δtime) over time intervals of 0–50 ms and 0–200 ms from the onset of contraction (time = 0). The onset of contraction was defined as 2.5% of the highest torque in each trial (Aagaard et al., 2002). In the patients group, MVC and RFD of each side were used for statistical analyses. For the control group, the mean values of right- and left-limb MVC and RFD were used for statistical analyses. MVC (Nm/kg) and RFD (Nm/s/kg) were expressed as the value divided by body weight. All analyses were performed using LabChart 7 (LabChart 7, ADInstruments Japan, Nagoya, Aichi, Japan).

2.4. Statistical analysis

Data are presented as mean ± SD or number. Any differences between patient and control groups were tested by the unpaired *t*-test or chi-square test. Differences in MVC and RFD between affected vs. unaffected sides in the patient group were tested by paired *t*-test. $P < 0.05$ was considered statistically significant. All statistical analyses were performed using the EZR (EZR, Saitama Medical Center, Jichi Medical University, Omiya, Saitama, Japan) (Kanda, 2013).

3. Results

Participant characteristics, including age ($p = 0.97$), sex ($p = 0.27$), and body weight ($p = 0.60$), did not significantly differ between the groups (Table 1). The patient group had no or slight paresis (BRS > IV) of the lower extremity on the affected side.

Fig. 1 shows the average torque responses in the patient and control groups. MVC on the affected side was significantly lower than MVC on the unaffected side (affected: 1.31 ± 0.54 Nm/kg; unaffected: 1.51 ± 0.52 Nm/kg, $p < 0.01$; Fig. 2). However, no significant differences in MVC were observed between groups, for either the affected ($p = 0.09$) or the unaffected side ($p = 0.70$; control: 1.48 ± 0.37 Nm/kg).

On the other hand, significant differences in RFD over intervals of 0–50 ms (affected: 2.24 ± 2.15 Nm/s/kg; unaffected: 2.71 ± 2.63 Nm/s/kg, $p < 0.01$; Fig. 3) were observed between affected and unaffected sides in the patient group. However, RFD of 0–200 ms did not differ significantly between affected and unaffected sides in the patient group (affected: 3.22 ± 1.93 Nm/s/kg; unaffected: 3.66 ± 2.00 Nm/s/kg, $p = 0.09$; Fig. 3). Compared with the control group, the patient group had significantly lower RFD over intervals of 0–50 ms (32–38%; 7.10 ± 3.01 Nm/s/kg, both sides: $p < 0.01$; Fig. 3) and 0–200 ms (62–71%; 5.16 ± 1.43 Nm/s/kg, both sides: $p < 0.01$; Fig. 3) for both the affected and unaffected sides ($p < 0.01$).

Table 1
Participant characteristics.

Variables	Patients	Healthy adults	P values
Age (yrs)	67 ± 12	67 ± 8	0.97
Sex (men/women)	19/12	25/29	0.27
Body weight (kg)	60.9 ± 12.5	59.7 ± 10.2	0.60
Stroke type (hemorrhage/infarction)	9/22		
Side of hemiparesis (left/right)	16/15		
Time since stroke (days)	21 ± 8		
Brunnstrom stage of lower extremity	IV: 2, V: 12, VI: 17		
Maximum walking velocity (m/s)	1.28 ± 0.44		

Values are presented as the mean ± SD or n.

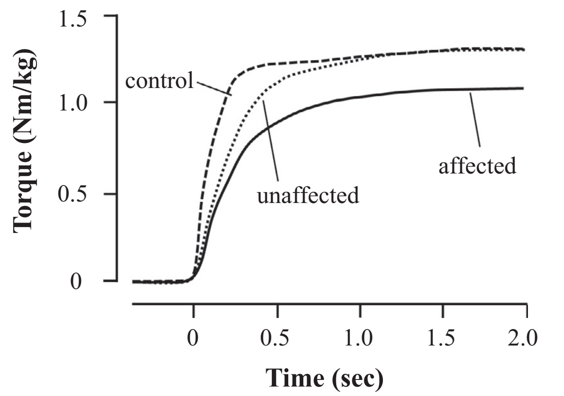

Fig. 1. Average torque-time curves for patient and control groups. Solid line represents the affected side and dotted line represents unaffected side in the patient group. The coarse dotted lines represent the control group.

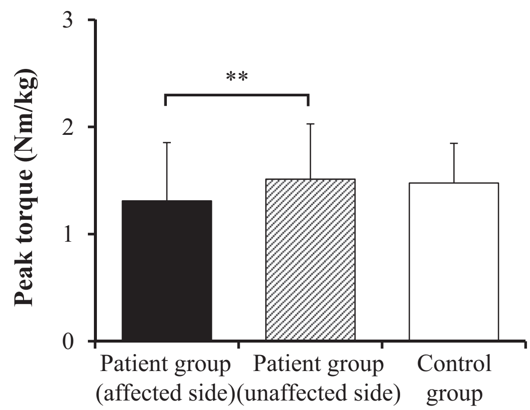

Fig 2. Peak torque during knee extension on the affected vs. unaffected side in patients with stroke and healthy adults. The closed bar represents the affected side in stroke patients. The hatched bar represents the unaffected side in stroke patients. The open bar represents healthy adults. ** $p < 0.01$.

4. Discussion

To the best of our knowledge, this is the first study to show a decrease in RFD of knee extensors in patients with history of acute stroke for both the affected and unaffected sides. Notably, patients enrolled in this study had no or slight disability (BRS > IV), and all the patients could walk independently. Patients in this study had good motor function, and the effect of disuse was small. There were no differences between patient and control groups in MVC on either side. However, knee extensor RFD of both sides markedly decreased in the patient group compared with that in the control group, both intervals of 0–50 ms and 0–200 ms. These findings suggest that the decrease in RFD was initiated during the acute phase of stroke, even in the stroke patients who had mild paresis without reduction of MVC. The decrease in RFD appears to be primarily influenced by neural, rather than muscular factors (e.g., disuse atrophy).

Our results showed that MVC was lower on the affected side than on the unaffected side, suggesting that the patients had paresis. However, MVC (as measured within one month after the onset of stroke) on the affected and unaffected sides was similar to that measured in age-matched healthy adults. These results suggest that the effect of disuse was limited and influenced by mainly neural factors.

Although RFD is influenced by neural drive (Aagaard et al., 2002; Klass et al., 2008), cross-sectional muscle area (Suetta et al., 2004), distribution of fiber type (Korhonen et al., 2006), and stiffness of the tendinous structure (Reeves et al., 2003), neural drive is the most important factor with an effect on RFD (Aagaard, 2003). The summation of motor unit activity plays an important role during the developing phase. Moreover, it has been reported that RFD has different physiological parameters at different intervals (Andersen and Aagaard. 2006). For instance, RFD in the early phase is influenced by twitch characteristics (Andersen and Aagaard. 2006), and mainly related to the firing rate of motor units (Maffiuletti et al., 2016). Delayed-phase RFD is related to maximum muscle strength (Andersen and Aagaard. 2006), suggesting the recruitment of motor units is predominant. In this study, RFD was calculated over the interval of 0–50 ms (early phase) and 0–200 ms (later phase), as proposed by Aagaard et al. (2002). Surprisingly, our results showed that the differences in RFD between patient and control groups were larger over the time interval of 0–50 ms compared with 0–200 ms, on both the affected and unaffected sides (RFD at 0–50 ms: 32–38% relative to healthy adults, RFD at 0–200 ms: 62–71% relative to healthy adults; Fig. 3). Chou et al. (2013) reported that the firing rate in the force-developing phase was reduced on the affected side compared with the unaffected side in chronic stroke patients, suggesting that the firing rate of motor units was impaired during the force-developing phase in stroke patients. Our findings suggest that a decrease in motor unit firing rate during knee extension may contribute to a decrease in knee extensor RFD in patients with history of acute stroke.

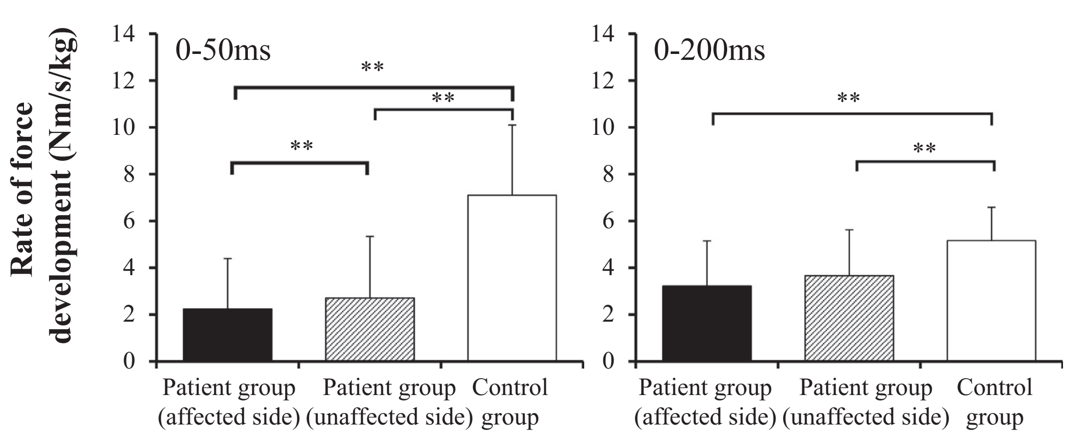

Fig. 3. Rate of knee extensor force development over time intervals of 0–50 ms and 0–200 ms, in patient and control groups. The closed bar represents the affected side in the patient group; the hatched bar represents the unaffected side in the patient group; the open bar represents the control group. ** $p < 0.01$.

Our results showed that RFD, which is the ability to produce instantaneous muscle activity during the early phase of muscle contraction, was substantially impaired on both sides during the acute phase of stroke, without any decrease in MVC. Our results suggest that stroke patients have poor ability to rapidly respond during sudden postural perturbation, which may restrict the performance of daily activities, even among patients with good motor function (as indicated by MVC). RFD is strongly associated with functional daily tasks such as walking (Clark et al., 2013; Maffiuletti et al., 2016; Mentiplay et al., 2018; Pohl et al., 2002; Takeda et al., 2018) and balance performance (Chang et al., 2005). Thus, RFD should receive attention during the acute phase of stroke in order to facilitate early rehabilitation, even in patients with satisfactory motor function.

4.1. Study limitations

Our study included no electromyography data or data about muscle atrophy. Thus, it is difficult to elucidate the reason for the observed decrease in RFD. Another limitation is that our study only examined the knee extensors and did not examine the other muscle groups that may be relevant to functional tasks such as walking. Further investigation is required to elucidate the RFD in post stroke patients.

5. Conclusion

We examined RFD of the knee extensors on both sides in independent ambulant patients with history of acute stroke with no or slight disability within one month post-stroke compared to age-matched healthy adults. Knee extensor RFD significantly decreased even in post stroke patients who had good motor function and limited muscle disuse, for both sides compared with that in age-matched healthy adults, without reduction in MVC on either side. These findings suggest that bilateral RFD should be measured in order to understand acute-phase muscle characteristics in stroke patients, even those with good motor function.

Declaration of Competing Interest

We have no conflicts of interest to declare.

Acknowledgments

The authors thank all participants who took part in this study and the rehabilitation staff of Sagamihara Chuo Hospital and Kitasato University East Hospital for their support. We received no funding for this study.

References

Aagaard, P., Simonsen, E.B., Andersen, J.L., Magnusson, P., Dyhre-Poulsen, P., 2002. Increased rate of force development and neural drive of human skeletal muscle following resistance training. J. Appl. Physiol. 93, 1318–1326.

Aagaard, P., 2003. Training-induced changes in neural function. Exerc. Sport Sci. Rev. 31, 61–67.

Andersen, L.L., Aagaard, P., 2006. Influence of maximal strength and intrinsic muscle contractile properties on contractile rate of force development. Eur. J. Appl. Physiol. 96, 46–52.

Chang, S.H., Mercer, V.S., Giuliani, C.A., Sloane, P.D., 2005. Relationship between hip abductor rate of force development and mediolateral stability in older adults. Arch. Phys. Med. Rehabil. 86, 1843–1850.

Chou, L.W., Palmer, J.A., Binder-Macleod, S., Knight, C.A., 2013. Motor unit rate coding is severely impaired during forceful and fast muscular contractions in individuals post stroke. J. Neurophysiol. 109, 2947–2954.

Clark, D.J., Manini, T.M., Fielding, R.A., Patten, C., 2013. Neuromuscular determinants of maximum walking speed in well-functioning older adults. Exp. Gerontol. 48, 358–363.

Fimland, M.S., Moen, P.M., Hill, T., Gjellesvik, T.I., Tørhaug, T., Helgerud, J., Hoff, J., 2011. Neuromuscular performance of paretic versus non-paretic plantar flexors after stroke. Eur. J. Appl. Physiol. 111, 3041–3049.

Horstman, A.M., Gerrits, K.H., Beltman, M.J., Koppe, P.A., Janssen, T.W., de Haan, A., 2010. Intrinsic properties of the knee extensor muscles after subacute stroke. Arch. Phys. Med. Rehabil. 91, 123–128.

Kanda, Y., 2013. Investigation of the freely-available easy-to-use software ''EZR'' (Easy R) for medical statistics. Bone Marrow Transpl. 48, 452–458.

Klass, M., Baudry, S., Duchateau, J., 2008. Age-related decline in rate of torque development is accompanied by lower maximal motor unit discharge frequency during fast contractions. J. Appl. Physiol. 104, 739–746.

Korhonen, M.T., Cristea, A., Alén, M., Häkkinen, K., Sipilä, S., Mero, A., Viitasalo, J.T., Larsson, L., Suominen, H., 2006. Aging, muscle fiber type, and contractile function in sprint-trained athletes. J. Appl. Physiol. 101, 906–917.

Maffiuletti, N.A., Aagaard, P., Blazevich, A.J., Folland, J., Tillin, N., Duchateau, J., 2016. Rate of force development: physiological and methodological considerations. Eur. J. Appl. Physiol. 116, 1091–1116.

Mentiplay, B.F., Tan, D., Williams, G., Adair, B., Pua, Y.H., Bower, K.J., Clark, R.A., 2018. Assessment of isometric muscle strength and rate of torque development with hand-held dynamometry: test-retest reliability and relationship with gait velocity after stroke. J. Biomech. 75, 171–175.

Pohl, P.S., Duncan, P., Perera, S., Long, J., Liu, W., Zhou, J., Kautz, S.A., 2002. Rate of isometric knee extension strength development and walking speed after stroke. J. Rehabil. Res. Dev. 39 (6), 651–658.

Reeves, N.D., Maganaris, C.N., Narici, M.V., 2003. Effect of strength training on human patella tendon mechanical properties of older individuals. J. Physiol. 548, 971–981.

Suetta, C., Aagaard, P., Rosted, A., Jakobsen, A.K., Duus, B., Kjaer, M., Magnusson, S.P., 2004. Training-induced changes in muscle CSA, muscle strength, EMG, and rate of force development in elderly subjects after long-term unilateral disuse. J. Appl. Physiol. 97, 1954–1961.

Takeda, K., Tanabe, S., Koyama, S., Shomoto, K., Naoi, Y., Sakurai, H., Kanada, Y., 2018. Relationship between the rate of force development in knee extensor muscles and gait speed in patients with chronic stroke: a cross-sectional study. NeuroRehabilitation 43, 425–430.