

Original Article

Neuromuscular Activity During Volitional Tasks Differs from Reflex Responses

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Abstract

Objective: Persistent neuromuscular deficits are common following anterior cruciate ligament (ACL) injury and rehabilitation. Altered knee muscle activity has been reported during volitional tasks such as stair descent and reflex responses elicited by artificial tibial translation (TT). This study examined whether muscle activation patterns during these tasks reflect overlapping aspects of neuromuscular control. **Methods:** Cross-sectional secondary analysis of a heterogeneous cohort of $n=104$ participants. Electromyographic (EMG) activity of the vastus medialis (VM), vastus lateralis, biceps femoris, and semitendinosus was recorded bilaterally in ACL-reconstructed, conservatively treated ACL-deficient, and ACL-uninjured participants. EMG was assessed during pre-activity and weight acceptance (WA) during stair descent and during TT across four time windows (50 ms before to 95 ms after perturbation onset). Normalized root mean square values were calculated for each muscle, limb, and movement phase. Spearman rank correlations were calculated using a Bonferroni-corrected significance level of $\alpha=0.0031$. **Results:** Only one weak correlation remained significant after Bonferroni correction: VM activity during WA and TT in the late reflex interval (60-95 ms) ($r_s=0.306$, $p<0.001$). **Conclusion:** The weak associations observed suggest that stair descent and TT assess largely distinct aspects of volitional and reflex-related neuromuscular control and may provide complementary information.

Keywords: ACL, Artificial Tibial Translation, Correlation, Neuromuscular Activity, Stairway Descent

Introduction

Rupture of the anterior cruciate ligament (ACL) is a common injury in physically active people between the ages of 18 and 65 years¹ and can be treated either surgically or non-surgically. It is known that after ACL

reconstruction many athletes do not reach the same level of performance in sport as before the injury²⁻⁴. Moreover, the risk of suffering a reinjury to the reconstructed ACL or a contralateral ACL tear/rupture is high^{2,5-12} and can be 25 times greater than the risk of an initial ACL injury¹³.

To minimize this risk, actual research suggests conducting test batteries (physical performance tests) with return-to-sport (RTS) criteria to determine readiness to safely RTS¹⁴⁻²¹. A standardized clinical measure can reduce the risk of reinjury by 75-84%^{14,22}. But despite passing the RTS criteria, 10% suffer a second ACL injury²² and the risk of a contralateral ACL rupture increases²³. The problem could be that besides balance, strength and functional assessments, there is yet no valid clinical test to detect neuromuscular dysfunction. It is already known

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that there is a change in the neuromuscular activity of the knee muscles after ACL injury and its subsequent reconstruction during stair ambulation^{24,25} and reflex tests that provoke anterior tibial translation (TT)^{26–29}. These results suggest an increased risk of a second ACL injury, but so far there are no clear indications.

Both neuromuscular tasks have different demands. Stair ambulation is a volitional task, controlled by the person's goal and intention³⁰, whereas fast TT triggers reflex activity that cannot be controlled voluntarily³¹. These differences may justify investigating both tasks to evaluate neuromuscular performance and may provide complementary information for subsequent reinjury risk assessment, as both tasks may be related to or independent of each other.

Therefore, the aim of this study was to examine if there is a correlation between EMG activities during volitional tasks and reflex responses and thus to investigate whether both tests may provide complementary information during the RTS process. The hypothesis was that there is neither positive nor negative correlation between these two test situations.

Materials and Methods

Participants

Sample size calculation was based on a primary estimation according to the rationale described in Blasimann et al. 2023²⁵. As an exploratory secondary analysis, the sample size was determined for the primary injured vs. healthy comparison and not for the present research question, which represents a first investigation of this specific topic.

In total, 104 participants aged between 17 and 59 years were included in this cross-sectional cohort study if they were physically active³² ($\geq 2 \times 45$ minutes/week) and have either two intact ACLs or have had an ACL rupture, with or without reconstruction, 11 to 14 months before testing. ACL status in participants with an ACL rupture was evaluated using magnetic resonance imaging, whereas ACL status in healthy participants was assessed clinically. ACL conservatively treated as well as ACL reconstructed participants were each matched to the healthy participants. All participants were recruited at a single orthopedic clinical center. Exclusion criteria for all groups were: former knee pathology before ACL injury, injuries of the trunk or lower extremity, surgeries of the lower limb $\leq$ five years before the actual ACL injury, cardiac, neurologic or peripheral vascular disease, acute infection, alcohol abuse, current pain medication, thrombosis, dementia or pregnancy.

All participants with an ACL rupture were first clinically examined by an orthopedic surgeon to check their eligibility for participation in this study. A physiotherapist specialized in orthopedics gave comprehensive written and oral information about the study procedure. The

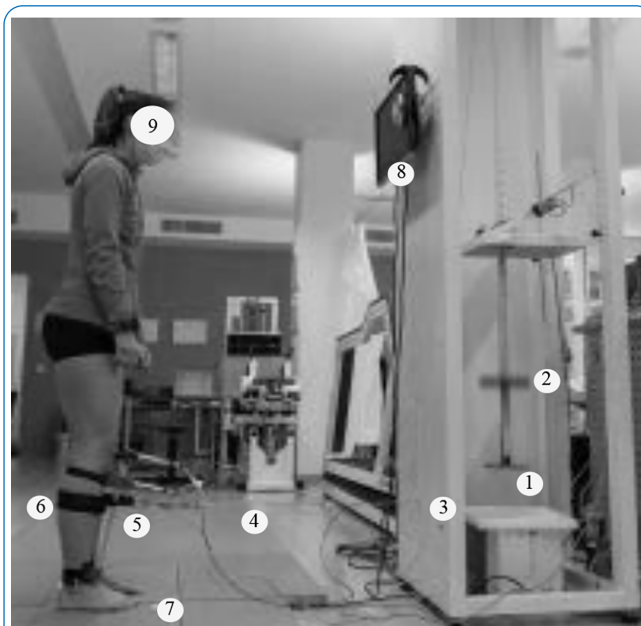


Figure 1. Rope and pulley system. 1: stopper, 2: falling barbell weight, 3: pulley, 4: rope, 5: force transducer, 6: band-sling, 7: force platform, 8: monitor, 9: headphones and attenuator.

STROBE 2007 statement (Strengthening the Reporting of Observational Studies in Epidemiology) was used for reporting the study³³.

Procedure

Participants were prepared for surface electromyographic (EMG) measurements. The skin was shaved, roughened with sandpaper, and cleaned with alcohol. Bipolar surface electrodes (Ambu BlueSensor, Ambu A/S, Ballerup, Denmark, Type P-OO-S, interelectrode distance: 20mm) were placed on the muscle bellies of vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF) and semitendinosus (ST) on both limbs, following the SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) recommendations³⁴. Validity and correct channel assignments were checked by isolated activation of each muscle and interelectrode impedance was controlled and kept $\leq 2\text{k}\Omega$ (Impedance meter D175, Digitimer®, Herfordshire, UK). The reference electrode was placed on the right patella. The transmission of the signal occurred across a differential-preamplifier (gain: 500, Input Impedance: 4000 M, Common Mode Rejection 90 dB at 60 Hz) to a telemetric main amplifier (PowerPack, pfitec, Endingen, Germany; Band-Pass Filter: 10 Hz – 1 kHz, Gain: 5.0, resultant overall gain: 2500) where the

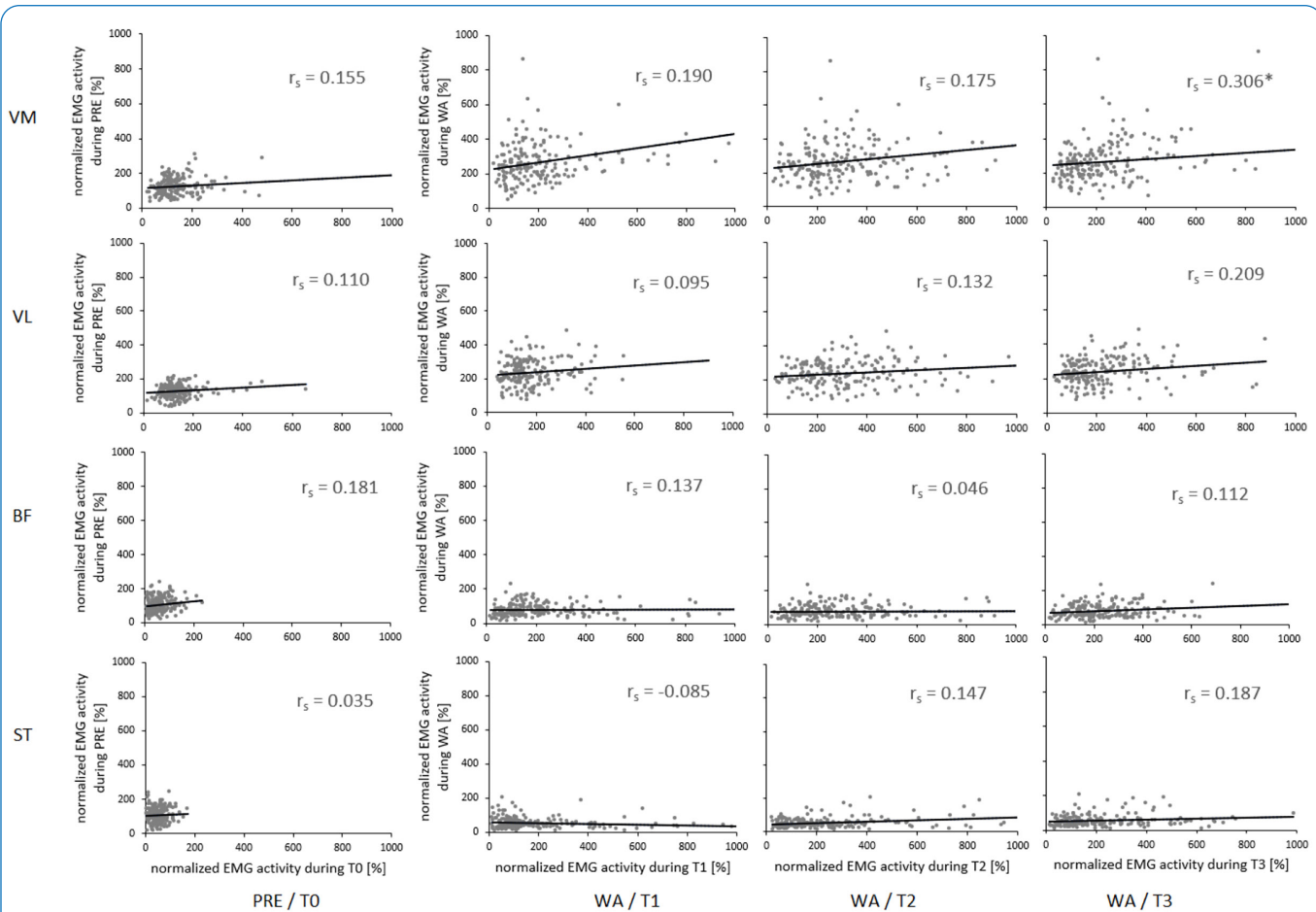


Figure 2. Correlation between stairway descent and tibial translation. r_s : Spearman's correlation coefficient. Lines are included for visualization purposes only. *: $p < 0.0031$ after Bonferroni correction. Abbreviations: PRE = pre-activity; WA = weight acceptance; VM = vastus medialis, VL = vastus lateralis, BF = biceps femoris, ST = semitendinosus; timeframes in relation to the onset of tibial translation: T0 = -50 to 0 ms, T1 = 20 to 40 ms, T2 = 40 to 60 ms, T3 = 60 to 95 ms.

signal was recorded with 2000 Hz for walking and stair ambulation and with 4000 Hz for the artificially induced TT³⁵. After conducting an analog/digital conversion (NI PCI 6355, National Instruments®, Austin, USA; 1.25 MS/s, 16 Bit) a LabVIEW®-based software (IMAGO Record, pfittec, Endingen, Germany) registered the signals.

The participants performed a 10-minute warm-up on a treadmill (quasar med, h/p/cosmos sports & medical GmbH, Nussdorf-Traunstein, Germany) at 5 km·h⁻¹. Underneath the treadmill were two force transducers (Typ KMB52, 10kN, MEGATRON Elektronik GmbH & Co. KG, Putzbrunn, Germany) which determined vertical forces to detect initial contact and gait cycle phases (weight acceptance, push-off). During the last two minutes, EMG signals were recorded.

Afterwards, the participants were asked to descend a

six-step-stairway ten times at a self-selected speed and always with the right foot first. The custom-made wooden staircase had a step height of 17.1 cm, a step depth of 29.0 cm and an inclination of 30.6°³⁶. There were two multi-component force plates (type 9286BA, Kistler Instrumente AG, Winterthur, Switzerland) embedded in the third and fourth steps, which were supported by a heavy metal frame. The force plates were used to record the changes in the ground reaction force, which will be used for analysis in later data processing.

For the reflex test, the participants had to stand with both feet on two force platforms (type 9286BA, Kistler Instrumente AG, Winterthur, Switzerland) with the knees in 30° flexion and with arms akimbo. Visual feedback by a computer monitor gave information about the distribution of the weight bearing between right and left extremity

Table 1. Timeframes of the EMG-signals (time in relation to initial contact (IC) or onset of the tibial translation).

	Treadmill walking	Stairway descent	Tibial translation
Gait cycles	One gait cycle (IC to IC)	-150 to 0 ms (PRE) Breaking phase (WA) Propulsion phase (PO)	
Timeframes	-50 to 0 ms (T0) 20 to 40 ms (T1) 40 to 60 ms (T2) 60 to 95 ms (T3)		-50 to 0 ms (T0) 20 to 40 ms (T1) 40 to 60 ms (T2) 60 to 95 ms (T3)
Abbreviations: IC = initial contact, PRE = pre-activity, WA = weight acceptance, PO = push-off.			

and the participants were invited to equalize the load. Additionally, headphones with music and an attenuator were worn to avoid acoustic anticipation. To induce a TT in posterior-anterior direction a rope and pulley system was used (eg, Figure 1)³¹. A rope transferred the impulse of a falling 2.5 kg barbell weight from a height of 1.0 m to the dorsal side of the tibial plateau generating an anterior TT³¹. The resulting force was monitored by a force transducer (type KM1506, 2kN, MEGATRON Elektronik GmbH & Co. KG, Putzbrunn, Germany), which was inserted between the rope and the band-sling.

Both legs were tested in randomized order (randomization.com). TT was applied 30 times per leg with a five-minute break after 15 repetitions. In between each stimulus, a break of about 30 seconds was taken to avoid impulse anticipation and to allow the participants to adjust the standing position. The setup was reconstructed and optimized based on the previous descriptions^{37,38}. Excellent reliability of the hamstring reflex responses was elucidated previously [BF: interclass correlation coefficients (ICCs) between 0.88 and 0.96; ST: ICCs between 0.87 and 0.95]³⁹.

All measurements were conducted in the Bern Movement Lab (Bern University of Applied Sciences, Switzerland) from March 2018 to July 2021.

Data Reduction

By using a LabVIEW® based software (IMAGO Process Master, pfitec, Emdingen, Germany), EMG data processing was performed. The signals from the treadmill walking test were broken down to determine the mean EMG activity for each muscle over 30 gait cycles. One gait cycle was defined as the timeframe between two initial contacts of the same limb. These data were further used to submaximally normalize the EMG data from the stairway descent. Additionally, the EMG-signals before and after the initial contact during treadmill walking were broken down into pre-activity (= T0; 50 to 0 ms before ground contact (GC)), short latency response (= T1; 20 to 40 ms after GC), medium latency response (= T2; 40

to 60 ms) and long latency response (= T3; 60 to 95 ms)^{31,37,38} (eg, Figure 2). These data were further used to submaximally normalize the EMG data from the reflex test. The EMG signals during the reflex test were broken down into the same timeframes (background activity = T0, 50 ms prior to the onset of TT; short latency response = T1, 20 to 40 ms after the onset of TT; medium latency response = T2, 40 to 60 ms; long latency response = T3, 60 to 95 ms)^{31,37,38} (eg, Table 1). The onset of the TT was defined by the signal of the force transducer between the rope and the band-sling. The movement cycles during stairway descent were divided into pre-activity (= PRE; 150 ms prior to the initial contact), weight acceptance (= WA; from the initial contact to the lowest applied vertical ground reaction force) and push-off (= PO; from lowest applied vertical ground reaction force until the foot left the ground)^{40,41} (eg, Table 1). This signal breakdown was done for 10 steps with each limb.

All signals were full-wave rectified and the raw EMG signals from the treadmill were additionally band-pass filtered at 10-500 Hz (Butterworth, 2nd order). For further processing, the root mean square (RMS) values for each phase and muscle were calculated and exported in Microsoft Excel® (Version 1911, Microsoft Corporation, Redmond, WA, USA). The individual mean activity was calculated for all muscles during the defined phases over the corresponding number of trials. For the submaximal normalization of the phases during stairway descent, the RMS values were normalized by the activation of the mean gait cycle during treadmill walking for each muscle and were expressed as percentages. A similar principle was applied to normalize the activity during TT. The timeframes T0 to T3 of each muscle during TT were normalized with equal timeframes during normal walking³⁹⁻⁴⁵.

After normalization, the mean and standard deviation (SD) over all participants in each timeframe for each muscle were calculated and checked for plausibility. If an individual value was higher or lower than twice the SD (stairway) or three times the SD (TT), it was tracked back to the raw EMG data and inspected for potential errors that may require recalculation of the outcome values. All

Table 2. Characteristics of participants.

	Group	n	Mean $\pm$ SD	95% CI
Age [years]	ACL-I	40	33.0 $\pm$ 8.97	30.2; 35.8
	ACL-R	38	32.0 $\pm$ 12.21	28.1; 35.9
	ACL-cons	26	37.9 $\pm$ 11.69	33.4; 42.4
	Total	104	33.9 $\pm$ 11.08	31.7; 36.0
Body height [cm]	ACL-I	40	175.1 $\pm$ 8.02	172.6; 177.6
	ACL-R	38	173.6 $\pm$ 6.25	171.6; 175.5
	ACL-cons	26	171.0 $\pm$ 8.06	167.9; 174.1
	Total	104	173.5 $\pm$ 7.53	172.0; 175.0
Body mass [kg]	ACL-I	40	70.6 $\pm$ 11.24	67.1; 74.1
	ACL-R	38	71.7 $\pm$ 11.19	68.2; 75.3
	ACL-cons	26	71.7 $\pm$ 15.07	65.9; 77.5
	Total	104	71.3 $\pm$ 12.18	69.0; 73.6
Activity [min]	ACL-I	40	284.9 $\pm$ 179.49	229.2; 340.5
	ACL-R	38	420.5 $\pm$ 264.77	336.3; 504.7
	ACL-cons	26	366.5 $\pm$ 159.86	305.0; 427.9
	Total	104	354.8 $\pm$ 217.05	313.0; 397.0

Abbreviations: cm = centimeter; kg = kilogram; min = minutes; n = number of participants; SD = standard deviation; CI = confidence interval; ACL = anterior cruciate ligament; I = intact; R = reconstructed; cons = conservative.

Table 3. Results.

		PRE/T0	WA/T1	WA/T2	WA/T3
VM	n	192	187	188	189
	r_s	0.155	0.190	0.175	0.306
	p	0.031	0.009	0.017	<.001
	CI	0.0159; 0.2941	0.0507; 0.3293	0.0353; 0.3147	0.1757; 0.4363
VL	n	191	187	190	189
	r_s	0.110	0.095	0.132	0.209
	p	0.129	0.198	0.070	0.004
	CI	-0.0312; 0.2512	-0.0482; 0.2382	-0.0088; 0.2728	0.0716; 0.3464
BF	n	190	189	190	191
	r_s	0.181	0.137	0.046	0.112
	p	0.013	0.060	0.532	0.123
	CI	0.0424; 0.3196	-0.004; 0.278	-0.097; 0.189	-0.0292; 0.2532
ST	n	191	185	184	185
	r_s	0.035	-0.085	0.147	0.187
	p	0.634	0.248	0.046	0.011
	CI	-0.1078; 0.1778	-0.2254; 0.0554	0.0045; 0.2895	0.0468; 0.3272

r_s : Spearman's correlation coefficient; p: p-value ; CI: 95% confidence interval. Abbreviations: PRE = pre-activity; WA = weight acceptance; VM = vastus medialis, VL = vastus lateralis, BF = biceps femoris, ST = semitendinosus; timeframes in relation to the onset of tibial translation: T0 = -50 to 0 ms, T1 = 20 to 40 ms, T2 = 40 to 60 ms, T3 = 60 to 95 ms.

inspected values were confirmed to be valid, and no data were excluded from the analysis²⁵.

Statistical Analysis

Participants were pooled into a single analytical cohort, and all statistical analyses were performed on the combined sample to preserve heterogeneity and maximize variability.

The EMG data were checked for normal distribution using the Shapiro-Wilk Test with an α -level of 0.1. Because most of the data deviated from normal distribution, the Spearman's rank correlation coefficient (r_s) and its p-value were calculated for each muscle to evaluate the relationship between PRE and TO as well as between WA and the timeframes T1 to 3. An r_s of zero indicated no correlation between outcome measures, an r_s of 0.00-0.25 was considered very low, an r_s of 0.26-0.49 low, an r_s of 0.50-0.69 moderate, an r_s of 0.70-0.89 high, and an r_s of 0.90 very high⁴⁶. The push-off phase had no corresponding timeframe in the reflex measurements, therefore it was not included in the analysis.

To account for multiple testing across all calculated correlations, a Bonferroni correction was applied to all tests. The initial α -level was set at 0.05, resulting in an adjusted overall significance threshold of $\alpha = 0.0031$ (0.05/16).

All statistical analyses were conducted using the jamovi software (Version 2.2.5.0, the jamovi project, retrieved from <https://www.jamovi.org>).

Results

Both legs ($n=208$) of 104 participants (51 women, 53 men) were included. 38 had an ACL reconstruction (ACL-R), 26 treated the ACL rupture conservatively (ACL-C) and 40 had two intact ACLs (ACL-I). Further details can be found in Table 2.

The correlation between EMG data of stairway descending and TT of the VM muscle between WA and T3 was low but statistically significant, which survived Bonferroni correction ($r_s = 0.306$; $p < 0.001$). All other correlations of the VM (PRE/TO, $p < 0.05$; WA/T1, $p < 0.01$; WA/T2, $p < 0.05$), VL (WA/T3, $p < 0.01$), BF (PRE/TO, $p < 0.05$) and ST (WA/T2 and WA/T3, $p < 0.01$) were very low and showed no statistical significance after Bonferroni correction (eg, Figure 2). Detailed information can be found in Table 3.

Discussion

The aim of this study was to examine if there is a relationship between volitional activities during a functional task (stairway descent) and reflex responses during a physiological task eliciting stretch reflex activity (TT). Results showed very low to low correlation between

PRE/WA and the timeframes TO to T3, except for a significantly low correlation between WA and T3. This may indicate that the neuromuscular control of the knee responds differently to various situations, especially during these timeframes, which offers the closest temporal comparability between volitional activities and reflex responses. Visual control is an important factor in all volitional movements for the accurate timing of muscle activity onset⁴⁷. The movement during stairway descent could be planned and the muscles could be preactivated. After an ACL injury, the muscle activity is changed^{24,25,29,48} and therefore the feedforward program is disturbed. If the visual control is missing, or the action is too fast for the visual reflex loop, a faster reflex arc must be used. This involuntary reaction is essential for all fast maneuvers in sports like cutting or landing. After an ACL injury, the reflex response is altered^{25,29,49} and therefore the feedback mechanism is changed. Because the two tasks in this study were based on different motor programs, no conclusion can be drawn from one situation to the other. In this case, volitional movement execution cannot be used to extrapolate behavior in involuntary reactions to an external perturbation. This implies the need to investigate both tasks to gain a better understanding of the voluntary activities during stairway walking as well as of the reflex response during a simulated injury mechanism.

Possible correlations would become apparent if subgroups were compared. It is for example suspected that there are gender-specific differences in neuromuscular activities^{38,50-52}. Thus, we cannot know if the results could be gender dependent. Furthermore, it is unknown whether healthy participants show the same neuromuscular pattern as injured ones during the two test situations. There is only one pilot study which investigated neuromuscular activity before injury and found altered neuromuscular activation patterns⁵³. Moreover, acute injury seems to alter reflex as well as voluntary neuromuscular control when patients and healthy individuals are compared⁴⁹.

This study has potential limitations that should be considered. As it is the first study to compare volitional activities during stairway descending and reflex responses during TT, comparisons with results from the literature are not possible. Therefore, the results of the present study should be interpreted with caution. Moreover, the EMG normalization could justifiably have been done by maximal voluntary isometric contraction. However, this technique also has its limitations⁵⁴. Submaximal normalization is more applicable to patients who may be unable to produce maximal forces after ACL reconstruction during a specific exercise and EMG-data are more stable than the normalization to the maximum voluntary contraction (MVC)⁵⁵. Another limitation is the standardization of the test situations. During stairway descent, the participants could select the ambulation speed. This might have a crucial influence on neuromuscular activity²⁹. However, if the speed would have been standardized, the normal gait pattern of the individuals might have changed accordingly.

During TT, the weight bearing was monitored for equal distribution between right and left extremities and the knees were adjusted for 30° flexion, but the anterior and posterior direction was uncontrolled and no further instruction for the trunk position (despite “hands akimbo”) was given. If the weight is more onto the heel or forefoot, the center of mass changes and results in more extended or flexed trunk position^{56–58}, which could affirm the activity of the hamstrings. Consequently, the starting position could have led to a different neuromuscular strategy. Moreover, the band-sling was placed at the proximal part of the shank over the triceps surae muscle, which could have influenced the activation of the hamstring muscles due to mechanical stimuli in the triceps surae Ia and II afferents³¹. Beyond these points, a further limitation of this study is that analyses were performed at the limb level, including bilateral observations from some participants. As a result, observations were not fully independent, which may have led to somewhat optimistic p-values and confidence intervals. However, the purpose of this exploratory study was to assess the magnitude of associations rather than to draw confirmatory statistical conclusions. As the observed correlations were consistently weak (maximum $r_s = 0.306$; <10% shared variance), participant-level sensitivity analyses would be unlikely to change the principal interpretation that reflex-related and volitional muscle activity exhibit only limited association and likely represent distinct aspects of neuromuscular control.

Taken together, the present findings provide evidence for task-specific differences in neuromuscular control between volitional and reflex-mediated conditions. However, they should be interpreted as an initial exploratory investigation of the relationship between these two motor control domains rather than as evidence for clinical application in RTS decision-making.

Further studies should focus on the sensitivity and specificity of both tests to determine which test can assess neuromuscular activity after an ACL-injury for a safe RTS. This would give more insights into protective and injury predisposing neuromuscular patterns. Both aspects might then be used in rehabilitation as well as in secondary prevention settings. Long-term follow-up studies are then necessary to prove the efficacy of those regimens.

Conclusion

There are different neuromuscular activation strategies during stairway descent (volitional) and TT (reflex responses). Therefore, the present findings suggest that both tests may provide complementary information and could be performed separately during rehabilitation to assess different aspects of volitional activity and reflex responses, thereby providing a more comprehensive assessment of deficits in neuromuscular control. Further studies are warranted to determine the clinical utility of these two tests in identifying deficits that may be associated

with an increased risk of reinjury and to evaluate their role in the RTS decision-making process. Furthermore, neuromuscular control assessed by EMG is still not easily available in daily practice. Therefore, the development of easy to use and easy to interpretable devices is warranted before these assessments can be implemented in clinical practice.

Ethics Approval

This study was approved by the Ethical Committee of the Canton Bern, Switzerland (No. 213/15, 02.11.2015) and was carried out in accordance with the Declaration of Helsinki.

Consent to Participate

Written informed consent was obtained from all participants.

Author's Contributions

Conceptualization, HBa; ABl, PHe; Acquisition of data, ABl; Analysis of data, AGE, HBa, MAI; Interpretation of data, AGE, HBa, MAI; Writing—reviewing and editing, AGE, HBa; Supervision, HBa, ABl, ABu, PHe; All authors approved the final version of the manuscript.

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