Journal of Electromyography and Kinesiology 23 (2013) 1283–1288

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Validity and reliability of isometric, isokinetic and isoinertial modalities for the assessment of quadriceps muscle strength in patients with total knee arthroplasty

K. Lienhard [a,b,c], S.P. Lauermann [a,b], D. Schneider [a,b], J.F. Item-Glatthorn [a], N.C. Casartelli [a,d]
N.A. Maffiuletti [a,*]

[a] Neuromuscular Research Laboratory, Schulthess Clinic, Zurich, Switzerland
[b] Institute of Human Movement Sciences and Sport, ETH, Zurich, Switzerland
[c] Laboratory of Human Motricity, Education, Sport and Health (LAMHESS) – EA 6309, University of Nice Sophia Antipolis, Nice, France
[d] INSERM U1093 – Cognition, Action and Sensory Plasticity, University of Burgundy, Dijon, France

ARTICLE INFO

Article history:
Received 8 May 2013
Received in revised form 3 September 2013
Accepted 12 September 2013

Keywords:
Arthroplasty
Muscle strength
Self report
Reproducibility of results

ABSTRACT

Reliability of isometric, isokinetic and isoinertial modalities for quadriceps strength evaluation, and the relation between quadriceps strength and physical function was investigated in 29 total knee arthroplasty (TKA) patients, with an average age of 63 years. Isometric maximal voluntary contraction torque, isokinetic peak torque, and isoinertial one-repetition maximum load of the involved and uninvolved quadriceps were evaluated as well as objective (walking parameters) and subjective physical function (WOMAC). Reliability was good and comparable for the isometric, isokinetic, and isoinertial strength outcomes on both sides (intraclass correlation coefficient range: 0.947–0.966; standard error of measurement range: 5.1–9.3%). Involved quadriceps strength was significantly correlated to walking speed (r range: 0.641–0.710), step length (r range: 0.685–0.820) and WOMAC function (r range: 0.575–0.663), independent from the modality ($P < 0.05$). Uninvolved quadriceps strength was also significantly correlated to walking speed (r range: 0.413–0.539), step length (r range: 0.514–0.608) and WOMAC function (r range: 0.374–0.554) ($P < 0.05$), except for WOMAC function/isokinetic peak torque ($P > 0.05$). In conclusion, isometric, isokinetic, and isoinertial modalities ensure valid and reliable assessment of quadriceps muscle strength in TKA patients.

1. Introduction

Patients with total knee arthroplasty (TKA) suffer from quadriceps muscle weakness (i.e., insufficient strength) that can persist up to several years after surgery (Silva et al., 2003; Meier et al., 2008). This muscular deficit is often characterized as a side-to-side asymmetry, which is normally evaluated by calculating percent differences in maximal muscle strength between the involved and the uninvolved quadriceps (Valtonen et al., 2009; Maffiuletti et al., 2010). Adequate levels of quadriceps strength are of paramount importance for patients after TKA, as muscle strength is one of the major determinants of physical function and health-related quality of life in this population (Mizner et al., 2005b; Mizner and Snyder-Mackler, 2005; Maffiuletti et al., 2010). Therefore, quadriceps muscle strength of TKA patients should be determined using valid and reliable testing modalities, which entail the measuring device itself (dynamometer), the stability of the patient being measured, the procedure for conducting the measurements, and the main outcome measure.

Although quadriceps muscle strength of TKA patients has been increasingly assessed in the last two decades (Walsh et al., 1998; Mizner et al., 2003; Silva et al., 2003; Valtonen et al., 2009; Swank et al., 2011), there is no consensus among researchers and clinicians regarding the most valid test modality (that is, the modality considered most reliable and best related to physical function). Quadriceps muscle strength of TKA patients has been prevalently assessed during short (3–5 s) static contractions, of which the main outcome is isometric maximal voluntary contraction (MVC) torque (Mizner et al., 2003; Silva et al., 2003), or during slow isokinetic concentric contractions, of which the main outcome is isokinetic peak torque (Walsh et al., 1998; Valtonen et al., 2009; Swank et al., 2011). Isometric and isokinetic testing modalities are generally selected due to their reliability (Kean et al., 2010; Staehli et al., 2010), objectivity and safety, even though their validity has not been amply explored in patients with TKA. An alternative option for quantifying quadriceps strength relies on the use of dynamic constant external resistance devices (formerly denoted

* Corresponding author. Tel.: +41 44 385 7579; fax: +41 44 385 7590.
E-mail address: nicola.maffiuletti@kws.ch (N.A. Maffiuletti).

1050-6411/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jelekin.2013.09.004

as "isotonic"; hereafter referred to as "isoinertial"), such as conventional leg extension machines, that are often readily available, relatively inexpensive, and do not require any kind of data collection and post-processing (as opposed to isometric and isokinetic testing). However, isoinertial one-repetition maximum (1-RM) load has, to our knowledge, never been quantified in TKA patients, despite the fact that its evaluation has been shown to be both valid and reliable in healthy elderly subjects (Schroeder et al., 2007; Verdijk et al., 2009). It is therefore imperative to verify the validity of isoinertial quadriceps strength testing in TKA patients and to compare it to the most common strength testing modalities (i.e., isometric and isokinetic).

Therefore, the main aim of this methodological study was to examine the validity and reliability of isometric, isokinetic, and isoinertial modalities for the evaluation of quadriceps muscle strength in patients with TKA, with special emphasis on isoinertial testing. Construct validity was investigated by correlating strength outcomes to subjective and objective physical function outcomes, whereas reliability was evaluated using a test–retest design. We assessed both the involved (operated) and the uninvolved (contralateral, nonoperated) knee, as muscle strength of the latter has been shown to be an important predictor of function after TKA (Zeni and Snyder-Mackler, 2010).

2. Methods

2.1. Participants

Twenty-nine TKA patients (12 women, 17 men), who were selected from postoperative lists of our clinic, were included in this study (Table 1). The sample size was determined based on the recommendations of Fleiss (1986), which state that 15–20 subjects are required for estimating the reliability of a quantitative variable. The main inclusion criterion was unilateral TKA, implanted 3–12 months prior to the assessments (mean ± SD: 6.4 ± 1.8 months). Exclusion criteria consisted of additional injuries or surgeries in the lower limbs, cardiac or respiratory diseases, and the inability to walk without walking aids. All patients were provided with written information about the content of the study, and informed consent was obtained prior to the experiments. The local Ethics Committee gave approval for this study (KEK-ZH-NR: 2010-0095/0).

2.2. Experimental protocol

Each patient performed two quasi-identical testing sessions (hereafter referred to as test and retest), separated by a time interval of 2–8 days (Baumgartner and Jackson, 1987), during which lifestyle (including physical activity level) and medications were kept constant. We used a series of validated assessments, which included the subjective evaluation of physical function with a self-reported questionnaire (test only), the objective evaluation of walking function (test and retest), and the evaluation of muscle strength of the involved and uninvolved quadriceps using isometric, isokinetic, and isoinertial testing modalities (test and retest). Within each testing session, the assessment of maximal muscle strength always preceded the evaluation of submaximal walking function. Strength testing modalities were presented in a randomized order at the first test session; within each modality, the involved and uninvolved sides were also presented in a random fashion. The same order was then maintained (on an individual basis) during retest. Construct validity of isometric, isokinetic and isoinertial strength assessment modalities was examined by correlating respective strength outcomes to questionnaire scores (subjective physical function) and walking ability (objective physical function), as recently realized by Aalund et al. (2013). Reliability of isometric, isokinetic and isoinertial strength outcomes was examined by comparing data between the two test sessions.

Table 1
Demographic, anthropometric, and functional characteristics of the TKA patients.

	Mean ± SD (n = 29)
Age (years)	63 ± 6
Height (cm)	170 ± 8
Weight (kg)	79 ± 18
BMI (kg/m^2)	27 ± 5
WOMAC function (0 = worst; 100 = best)	90.5 ± 10.0
Walking speed (m/s)	1.37 ± 0.16
Step length (cm) – involved side	73.5 ± 6.2
Step length (cm) – uninvolved side	72.8 ± 7.3

BMI, body mass index; WOMAC, Western Ontario and McMaster Osteoarthritis Index.

2.3. Assessment of physical function

2.3.1. Self-reported questionnaire

Subjective physical function was evaluated using the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) (Stucki et al., 1996; Roos and Lohmander, 2003). The WOMAC covers three patient-relevant dimensions: pain (5 items), stiffness (2 items) and physical function (17 items), while only the physical function dimension was considered in this study. All the items present five possible answer options on a 5-point Likert scale ranging from 0 (no problems) to 4 (extreme problems). The main outcome was the total score of physical function that was calculated as the sum of the 17 items. This was subsequently transformed to a 0–100 scale, with zero representing worst function and 100 representing best function.

2.3.2. Walking

Walking function was evaluated with an electronic mat (GAITRite, CIR System Inc., Clifton, NJ, USA) which has been shown to provide valid (Bilney et al., 2003) and reliable (Menz et al., 2004) spatiotemporal gait parameters. Participants wore flat-soled shoes and were asked to walk on the 8-m mat at a self-selected normal velocity ("walk at a pace that is comfortable for you"). Patients performed one practice trial for familiarization followed by three test trials. Data from the three trials were consistently averaged for subsequent analyses. All trials began and ended approximately 2 m from the mat to ensure constant walking velocity. Recorded data (sampling frequency: 80 Hz) were processed into footfall patterns with a specific software (GAITRite Gold, Version 3.2b, CIR Systems Inc., Clifton, NJ, USA). The main outcomes were walking velocity (Mizner and Snyder-Mackler, 2005) and step length of the involved and uninvolved side (Maffiuletti et al., 2008).

2.4. Assessment of quadriceps muscle strength

2.4.1. Isometric strength

Patients were seated on the chair of an isokinetic dynamometer (Biodex System 2, Biodex Medical Systems, Shirley, NY, USA) with a trunk-thigh angle of about 90° (Fig. 1A). The tested knee was fixed at 60° of flexion (0° = knee fully extended) which corresponds to the joint position where maximal quadriceps force-generating capacity is commonly observed (Thorstensson et al., 1976). A series of non-elastic straps were buckled across shoulders and pelvis to minimize body movements during testing. Additionally, participants were consistently asked to fold their arms in front of the chest. The rotational axis of the dynamometer was visually aligned to the lateral femoral condyle. The leg was attached to the dynamometer lever arm with a strap positioned 2–3 cm proximal to

Fig. 1. Assessment of (A) isometric maximal voluntary contraction (MVC) torque, (B) isokinetic peak torque, and (C) isoinertial one-repetition maximum (1-RM) load.

the lateral malleolus. The gravity compensation procedure was performed according to the instructions of the manufacturers. Participants completed two to three familiarization trials at 40–80% of their maximal strength followed by three MVCs, where the main instruction was "contract as hard as you can". The duration of each MVC was 5 s and short rest periods of 45 s were interspersed between trials. We extracted the highest recorded MVC torque (sampling frequency: 100 Hz) from each of the three trials, and then averaged them.

2.4.2. Isokinetic strength

The isokinetic testing procedure was completed using the same dynamometer and participant positioning as during the isometric assessment, except that the dynamometer lever arm was set to move at an angular velocity of 60°/s throughout an 80° range of motion, from 90° to 10° of knee flexion (Fig. 1B). Participants completed three familiarization trials at 40–80% of their maximal strength, and were then requested to extend the knee "as fast and as hard as possible" three times throughout the entire range of motion, and to fully relax during knee flexion. The main outcome was the average peak torque of the three trials, which was obtained during the constant angular velocity period.

2.4.3. Isoinertial strength

Isoinertial muscle strength was assessed on a leg extension machine (Technogym, Gambettola, Italy) using a conventional 1-RM testing protocol (Tracy and Enoka, 2002). Patients were seated on the leg extension machine with a trunk–thigh angle of 90° (Fig. 1C). A wide velcro strap was fixed across the pelvis to minimize body movements during testing. The alignment between the rotational axis of the leg extension machine and the lateral femoral condyle was consistently verified. Knee extension range of motion was from 90° to 10° of flexion, and vice versa for knee flexion (during which patients were asked to relax). Patients were instructed to extend the knee "as fast and as hard as possible" and to lift the load to the upper range of motion. Identification of the 1-RM concentric load began with a load equivalent to 20% of body weight, and was progressively increased in steps of 5 kg, as determined in pilot experiments. Short rest periods of 45 s were interspersed between trials. Once the load could not be lifted through the entire range of motion, the last successful load was augmented by 2.5 kg to check if the patient was able to lift it. The trial with the highest load lifted through the full range of motion was retained. The main outcome was 1-RM load, which was reached for all patients between the second and the fourth trial on the involved side and between the third and the sixth trial on the uninvolved side.

2.5. Statistical analysis

Data were first checked for normality using Shapiro–Wilk tests and were all found to be normally distributed. Test–retest reliability of muscle strength outcomes was evaluated with two-way random effect intraclass correlation coefficients (ICC(2,1)) for relative reliability and absolute and relative (percentage) standard errors of measurement (SEM) for absolute reliability (Weir, 2005). Systematic differences between test and retest (bias) were identified using paired *t*-tests (two-tailed). Pearson's product-moment correlation coefficients (r) were calculated between strength outcomes (average of test and retest normalized to body weight) and physical function outcomes (average of test and retest). The significance level was set at $P < 0.05$ for all analyses.

3. Results

3.1. Test–retest reliability

Two patients did not perform the retest session due to illness (independent from the study); hence, their data were excluded

Table 2
Test–retest reliability of strength outcomes.

	Test (mean ± SD)	Retest (mean ± SD)	SEM (N m or kg)	SEM (%)	ICC (2,1)
Involved side (n = 27)					
Isometric MVC torque (N m)	128 ± 44	129 ± 42	7.9	6.2	0.965
Isokinetic peak torque (N m)	94 ± 37	97 ± 37	7.0	7.3	0.964
Isoinertial 1-RM load (kg)	29 ± 12	30 ± 12	2.7	9.3	0.947
Uninvolved side (n = 27)					
Isometric MVC torque (N m)	159 ± 48	162 ± 49	10.7	6.6	0.950
Isokinetic peak torque (N m)	132 ± 39	132 ± 39	7.4	5.6	0.963
Isoinertial 1-RM load (kg)	40 ± 11	40 ± 11	2.0	5.1	0.966

MVC, maximal voluntary contraction; 1-RM, one-repetition maximum; ICC, intraclass correlation coefficient; SEM, standard error of measurement.

Table 3
Correlations between physical function and strength outcomes.

	WOMAC function	Walking speed	Step length
Involved side (n = 29)			
Isometric MVC torque	**r = 0.618**	**r = 0.680**	**r = 0.685**
Isokinetic peak torque	**r = 0.663**	**r = 0.710**	**r = 0.733**
Isoinertial 1-RM load	**r = 0.575**	**r = 0.641**	**r = 0.820**
Uninvolved side (n = 29)			
Isometric MVC torque	**r = 0.548**	**r = 0.539**	**r = 0.603**
Isokinetic peak torque	r = 0.374	**r = 0.413**	**r = 0.514**
Isoinertial 1-RM load	**r = 0.554**	**r = 0.518**	**r = 0.608**

MVC, maximal voluntary contraction; 1-RM, one-repetition maximum; WOMAC, Western Ontario and McMaster Osteoarthritis Index. Bold numbers indicate significant correlations ($P < 0.05$).

from the reliability analyses. For both sides, muscle strength outcomes obtained in isometric, isokinetic and isoinertial conditions showed high ICC (range: 0.947–0.966) and relatively low SEM (range: 5.1–9.3%), with no apparent difference between testing modalities (Table 2). There was no significant bias between test and retest for all strength outcomes ($P > 0.05$).

3.2. Correlations with physical function

As a general observation, correlations between muscle strength and physical function outcomes were significant ($P < 0.05$, except for WOMAC function/isokinetic peak torque of the uninvolved side) and comparable for isometric, isokinetic and isoinertial testing modalities (Table 3). For the involved side, correlation coefficients ranged from 0.575 (WOMAC function/isoinertial 1-RM load) to 0.820 (step length/isoinertial 1-RM load). For the uninvolved side, correlation coefficients ranged from 0.374 (WOMAC function/isokinetic peak torque) to 0.608 (step length/isoinertial 1-RM load).

4. Discussion

The main findings of this methodological study are that both test–retest reliability and construct validity (relation with physical function) of quadriceps muscle strength outcomes were good and comparable among isometric, isokinetic and isoinertial testing modalities in TKA patients. Test–retest reliability was similar for the involved (operated) and uninvolved side, while construct validity results were better for the involved compared to the uninvolved quadriceps.

Although quadriceps muscle strength of patients after TKA has been increasingly assessed in the last few years (Walsh et al., 1998; Mizner et al., 2003; Silva et al., 2003; Valtonen et al., 2009; Swank et al., 2011), this is the first study in which test–retest reliability and construct validity of isometric MVC torque, isokinetic peak torque, and isoinertial 1-RM load were concomitantly assessed. Some other unique features of the present work were that muscle strength outcomes were correlated to both subjective and objective physical function outcomes (the construct being physical function), and reliability and validity analyses were accomplished for both the involved and the uninvolved side. In fact, it has recently been demonstrated that quadriceps weakness on the uninvolved side is an important long-term predictor of functional ability after TKA (Zeni and Snyder-Mackler, 2010).

The test–retest reliability results we obtained for isometric and isokinetic strength outcomes are similar to those reported in previous studies conducted with patients before and after TKA (ICC range: 0.93–0.98; SEM range: 8–9%) (Kean et al., 2010; Staehli et al., 2010). Reproducibility of isoinertial muscle strength has, to the best of our knowledge, never been investigated in TKA patients, while its assessment has actually been shown to be reliable in untrained middle-aged and elderly individuals (Levinger et al., 2009; Amarante do Nascimento et al., 2013). Interestingly, reliability results were comparable for the involved and uninvolved quadriceps, despite side-to-side differences in absolute muscle strength (20–30% depending on the test modality) and probably also in motivational/perceptual factors (e.g., fear of pain), although this was not verified in the present study. Taken as a whole, the present results establish the excellent test–retest reliability of isometric, isokinetic and isoinertial quadriceps strength outcomes in patients with TKA, thereby confirming that the three modalities can be used with confidence (though not interchangeably) to evaluate strength changes over time for both the involved and the uninvolved side.

Similar to the reliability findings, correlation coefficients between muscle strength and physical function outcomes were equally high for the isometric, isokinetic and isoinertial modalities. Isometric knee extension strength has previously been associated with performance-based measures of physical function in patients after TKA (Mizner and Snyder-Mackler, 2005; Yoshida et al., 2008; Kauppila et al., 2009; Holm et al., 2010; Aalund et al., 2013). More specifically, correlations similar to those reported in this study have been observed between isometric strength and objective physical function outcomes such as walking speed ($r = 0.51$) (Aalund et al., 2013), 6-min walking distance ($r = 0.76$) (Yoshida et al., 2008), and timed up and go time (r range: $|0.43|–|0.59|$) (Mizner and Snyder-Mackler, 2005; Yoshida et al., 2008). Isometric MVC strength has also been shown to be related to subjective physical function (WOMAC function), with a slightly lower correlation ($r = -0.32$) (Aalund et al., 2013) than the ones found in the present study. To our knowledge, no attempts have been made to examine the potential correlation between physical performance and isoinertial or isokinetic strength in patients after TKA. Our results show that subjective and objective physical function of patients with TKA are significantly related to quadriceps strength, regardless of the testing modality. Although we acknowledge that correlation does not necessarily imply causation, an improvement in postoperative quadriceps strength for TKA patients (even several weeks after surgery), would likely result in a better functional ability for activities of daily living.

Another interesting result emerging from our study is that muscle strength of the uninvolved side and walking parameters (walking speed and step length) were significantly related, although with lower correlation coefficients compared to the involved side. This observation substantiates the important role of the contralateral nonoperated quadriceps of TKA patients, which has received increasing attention over the past few years (see e.g., Zeni and Snyder-Mackler, 2010). In fact, the uninvolved side may play a major role in daily functioning during the first months after TKA surgery, and this could explain, at least in part, the observed correlation between strength and walking function in our patients. This is partially supported by the recent study of Mizner et al. (2005a), who suggested that the postoperative decline in quadriceps muscle strength on the operated side was expected to place more emphasis on the contralateral uninvolved side as an important contributor to objective physical function (stair climbing ability in particular). Interestingly, as soon as quadriceps weakness on the operated side was resolved (approximately 6 months after TKA surgery), both sides were equally important to account for functional performance (Mizner et al., 2005a).

One limitation of this study is that quadriceps muscle strength was assessed using isometric and concentric single-joint contractions, whereas in daily activities such as walking and stair climbing, concentric–eccentric multi-joint contractions predominate. Moreover, we used an open-chain exercise model (leg extension) for evaluating quadriceps strength in a valid way, even though such movement pattern is rare in daily activities. Therefore, the correlations we observed between strength and physical function could be potentially improved by the implementation of concentric–eccentric closed-chain multi-joint strength or even power testing (e.g., on a leg press machine) (Aalund et al., 2013), which have been shown to be both valid and reliable in older adults (Phillips et al., 2004; Schroeder et al., 2007; Verdijk et al., 2009). Another limitation of the current study is that quadriceps muscle strength was not evaluated within the functional range of motion utilized when walking. Even though this probably affected the correlational analyses, we preferred to quantify the maximum force generating capacity of the quadriceps at/close to the optimal muscle length and therefore to use conventional knee angles and procedures.

In conclusion, we have demonstrated that isometric, isokinetic, and isoinertial modalities provide valid and reliable data for the assessment of involved and uninvolved quadriceps strength in patients after TKA. From a practical point of view, this implies that quadriceps strength testing in both clinical practice and research settings can be performed with whatever available modality. Isoinertial assessment of muscle strength, which has been overlooked in the past, represents a valid alternative to isometric and isokinetic testing because it is easily and quickly administered, requires little skill involvement, no data processing and prior calibration, and is relatively inexpensive. Moreover, considering that isoinertial 1-RM load could be accurately estimated by means of submaximal and indirect testing procedures (Reynolds et al., 2006), this would nicely be integrated into routine clinical examination of quadriceps muscle strength of TKA patients.

5. Conflicts of interest

None declared.

References

Aalund PK, Larsen K, Hansen TB, Bandholm T. Normalized knee-extension strength or leg-press power after fast-track total knee arthroplasty: which measure is most closely associated with performance-based and self-reported function? Arch Phys Med Rehabil 2013;94(2):384–90.

Amarante do Nascimento M, Borges Januario RS, Gerage AM, Mayhew JL, Cheche Pina FL, Cyrino ES. Familiarization and reliability of one repetition maximum strength testing in older women. J Strength Cond Res 2013;27(6):1636–42.

Baumgartner TA, Jackson AS. Measurement for evaluation in physical education and exercise science. 3rd ed. Dubuque: Brown; 1987.

Bilney B, Morris M, Webster K. Concurrent related validity of the GAITRite walkway system for quantification of the spatial and temporal parameters of gait. Gait Posture 2003;17(1):68–74.

Fleiss JL. Reliability of measurements. In: Fleiss JL, editor. The design and analysis of clinical experiments. New York: John Wiley & Sons; 1986. p. 2–31.

Holm B, Kristensen MT, Bencke J, Husted H, Kehlet H, Bandholm T. Loss of knee-extension strength is related to knee swelling after total knee arthroplasty. Arch Phys Med Rehabil 2010;91(11):1770–6.

Kauppila A-M, Kyllonen E, Mikkonen P, Ohtonen P, Laine V, Siira P, et al. Disability in end-stage knee osteoarthritis. Disabil Rehabil 2009;31(5):370–80.

Kean CO, Birmingham TB, Garland SJ, Bryant DM, Giffin JR. Minimal detectable change in quadriceps strength and voluntary muscle activation in patients with knee osteoarthritis. Arch Phys Med Rehabil 2010;91(9):1447–51.

Levinger I, Goodman C, Hare DL, Jerums G, Toia D, Selig S. The reliability of the 1RM strength test for untrained middle-aged individuals. J Sci Med Sport 2009;12(2):310–6.

Maffiuletti NA, Gorelick M, Kramers-de Quervain I, Bizzini M, Munzinger JP, Tomasetti S, et al. Concurrent validity and intrasession reliability of the IDEEA accelerometry system for the quantification of spatiotemporal gait parameters. Gait Posture 2008;27(1):160–3.

Maffiuletti NA, Bizzini M, Widler K, Munzinger U. Asymmetry in quadriceps rate of force development as a functional outcome measure in TKA. Clin Orthop Relat Res 2010;468(1):191–8.

Meier W, Mizner RL, Marcus RL, Dibble LE, Peters C, Lastayo PC. Total knee arthroplasty: muscle impairments, functional limitations, and recommended rehabilitation approaches. J Orthop Sports Phys Ther 2008;38(5):246–56.

Menz HB, Latt MD, Tiedemann A, Mun San Kwan M, Lord SR. Reliability of the GAITRite walkway system for the quantification of temporo-spatial parameters of gait in young and older people. Gait Posture 2004;20(1):20–5.

Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. J Orthop Res 2005;23(5):1083–90.

Mizner RL, Stevens JE, Snyder-Mackler L. Voluntary activation and decreased force production of the quadriceps femoris muscle after total knee arthroplasty. Phys Ther 2003;83(4):359–65.

Mizner RL, Petterson SC, Snyder-Mackler L. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. J Orthop Sports Phys Ther 2005a;35(7):424–36.

Mizner RL, Petterson SC, Stevens JE, Axe MJ, Snyder-Mackler L. Preoperative quadriceps strength predicts functional ability one year after total knee arthroplasty. J Rheumatol 2005b;32(8):1533–9.

Phillips WT, Batterham AM, Valenzuela JE, Burkett LN. Reliability of maximal strength testing in older adults. Arch Phys Med Rehabil 2004;85(2):329–34.

Reynolds JM, Gordon TJ, Robergs RA. Prediction of one repetition maximum strength from multiple repetition maximum testing and anthropometry. J Strength Cond Res 2006;20(3):584–92.

Roos EM, Lohmander LS. The Knee injury and Osteoarthritis Outcome Score (KOOS): from joint injury to osteoarthritis. Health Qual Life Outcomes 2003;1:64.

Schroeder ET, Wang Y, Castaneda-Sceppa C, Cloutier G, Vallejo AF, Kawakubo M, et al. Reliability of maximal voluntary muscle strength and power testing in older men. J Gerontol 2007;62(5):543–9.

Silva M, Shepherd EF, Jackson WO, Pratt JA, McClung CD, Schmalzried TP. Knee strength after total knee arthroplasty. J Arthroplasty 2003;18(5):605–11.

Staehli S, Glatthorn JF, Casartelli N, Maffiuletti NA. Test–retest reliability of quadriceps muscle function outcomes in patients with knee osteoarthritis. J Electromyogr Kinesiol 2010;20(6):1058–65.

Stucki G, Meier D, Stucki S, Michel BA, Tyndall AG, Dick W, et al. Evaluation of a German version of WOMAC (Western Ontario and McMaster Universities) Arthrosis Index. Z Rheumatol 1996;55(1):40–9.

Swank AM, Kachelman JB, Bibeau W, Quesada PM, Nyland J, Malkani A, et al. Prehabilitation before total knee arthroplasty increases strength and function in older adults with severe osteoarthritis. J Strength Cond Res 2011;25(2):318–25.

Thorstensson A, Grimby G, Karlsson J. Force–velocity relations and fiber composition in human knee extensor muscles. J Appl Physiol 1976;40(1):12–6.

Tracy BL, Enoka RM. Older adults are less steady during submaximal isometric contractions with the knee extensor muscles. J Appl Physiol 2002;92(3):1004–12.

Valtonen A, Pöyhönen T, Heinonen A, Sipilä S. Muscle deficits persist after unilateral knee replacement and have implications for rehabilitation. Phys Ther 2009;89(10):1072–9.

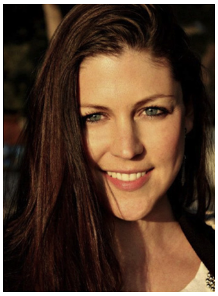
Verdijk LB, van Loon L, Meijer K, Savelberg HHCM. One-repetition maximum strength test represents a valid means to assess leg strength in vivo in humans. J Sports Sci 2009;27(1):59–68.

Walsh M, Woodhouse LJ, Thomas SG, Finch E. Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. Phys Ther 1998;78(3):248–58.

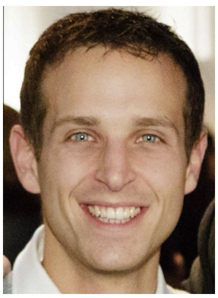
Weir JP. Quantifying test–retest reliability using the intraclass correlation coefficient and the SEM. J Strength Cond Res 2005;19(1):231–40.

Yoshida Y, Mizner RL, Ramsey DK, Snyder-Mackler L. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. Clin Biomech 2008;23(3):320–8.

Zeni JA, Snyder-Mackler L. Early postoperative measures predict 1- and 2-year outcomes after unilateral total knee arthroplasty: importance of contralateral limb strength. Phys Ther 2010;90(1):43–54.



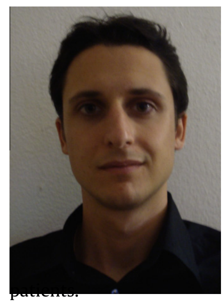
Karin Lienhard was born in Aarau, Switzerland, in 1983. She received her Master's degree in Human Movement Sciences with a Major in Motor Control in 2010 from the Federal Institute of Technology (ETH) in Zurich, Switzerland. For her Master's thesis, she investigated skeletal muscle strength and physical function in orthopaedic knee patients at the Neuromuscular Research Laboratory of the Schulthess Clinic in Zurich, Switzerland. At present, she is a Ph.D. student at the University of Nice Sophia Antipolis in France. Her main research interests concern the acute physiological adaptations to whole-body vibration exercise and electrophysiological signal processing.



Samuel P. Lauermann was born in St. Gallen, Switzerland, in 1984. He graduated in Human Movement Sciences in 2011 at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. He completed his Master's thesis at the Neuromuscular Research Laboratory of the Schulthess Clinic in Zurich, Switzerland. He is currently working as a Sales Representative for Medacta International SA. His current research interests include neuromuscular function and surgical techniques in orthopaedics (hip and knee joints).

David M. Schneider was born in St. Imier, Switzerland, in 1986. He graduated in Human Movement Sciences in 2011 at the University of Geneva, Switzerland. He is currently working as a sport scientist at the Swiss Sport Clinic in Bern, Switzerland. His current research interests include adaptions to high altitude in mountaineers and physiological performance analysis in cycling.

Julia F. Glatthorn was born in Chur, Switzerland, in 1981. She received the Master of Science degree in Human Movement Sciences with a Major in Exercise Physiology in 2008 from the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland. Since 2008 she is a Research Assistant and Laboratory Coordinator at the Neuromuscular Research Laboratory at the Schulthess Clinic in Zurich. Her research interests are the investigation of neuromuscular function in orthopaedic patients.



Nicola C. Casartelli was born in Mendrisio, Switzerland, in 1984. He studied Human Movement and Sport Sciences at the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland, where he received the BSc and MSc degree in 2007 and 2009, respectively. Presently, he is Research Assistant at the Neuromuscular Research Laboratory at the Schulthess Clinic in Zurich, Switzerland. He is a Ph.D. student at the INSERM U1093 laboratory (University of Burgundy, Dijon, France). His research interest is the study of the neuromuscular and physical function of orthopaedic patients, with particular focus on femoroacetabular impingement and hip patients.

Nicola A. Maffiuletti was born in Bergamo, Italy, in 1973. He received the Ph.D. degree in Sport Science in 2000 from the University of Burgundy in Dijon, France. He has been an Assistant Professor in the same University since 2001, and is currently Director of the Neuromuscular Research Laboratory at the Schulthess Clinic in Zurich, Switzerland. His current research interests include the exploration of neuromuscular function in orthopaedic patients and the clinical implementation of neuromuscular electrical stimulation. He is a member of the European College of Sport Science.