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Alpine Skiing With total knee ArthroPlasty (ASWAP): Muscular adaptations.

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Running head: Muscular adaptations after alpine skiing

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Abstract

This study investigated the effectiveness of recreational skiing as intervention to improve quadriceps muscle architecture, strength and antagonistic co-activation in patients with unilateral total knee arthroplasty (TKA). Hence, TKA patients were assigned to either an intervention group (IG) or control group (CG). The IG completed a 12 week guided skiing program whereas the CG was instructed not to change their daily routines for the same period and was not allowed to ski. Before, after the intervention / after an eight week retention period m. rectus femoris (RF) cross sectional area (CSA), m. vastus lateralis (VL) muscle thickness, fascicle length and pennation angle were measured with ultrasonography, while isometric (90° knee angle) knee extension, flexion torque and m. biceps femoris (BF) co-activation were assessed on an isokinetic dynamometer in 26 patients. There were significant and stable increases in RF CSA for the operated (10%; $P < 0.05$) and non-operated leg (12%; $P < 0.01$) after the training period in the IG whereas no changes were observed for the CG (all $P > 0.05$). There were no significant effects for other parameters (all $P > 0.05$). Overall, the skiing intervention was successful in increasing muscle mass in TKA older patients.

Keywords: strength, muscle weakness, ageing, sarcopenia

Introduction

For end-stage osteoarthritis, total knee arthroplasty (TKA) is a commonly used procedure which successfully reduces pain and activity limitations (Kösters et al., 2015). Although quadriceps strength is remarkably reduced (~60%) in the first month postoperatively, there is a subsequent increase in the following weeks until preoperative values are reached, six months post-TKA (Mizner et al., 2005; Stevens-Lapsley et al., 2010). However, results from recent publications indicate that muscle weakness persists after this period, leading to a 19-29% deficit in knee extensor strength of the operated (OP) leg compared to the non-operated (NOP) one (Lorentzen et al., 1999; Maffiuletti et al., 2010). At first sight, this imbalance seems to disappear after a year (Petterson et al., 2011), but using the NOP leg as a control may underestimate the magnitude of impairment since disuse stemming from osteoarthritis or inactivity could have weakened this leg (Farquhar & Snyder-Mackler, 2010). In fact, comparisons with healthy controls indicate a substantial strength deficit (20-35%) even three years after surgery (Walsh et al., 1998).

The persistent muscle weakness is often ascribed to the loss of muscle mass and/or neural impairments. Accordingly, muscle cross sectional area (CSA) and activation capacity follow a similar time course of recovery for quadriceps strength (Mizner et al., 2005; Petterson et al., 2011). However, activation capacity of both legs becomes comparable after 12 weeks post-surgery, while quadriceps CSA of the OP leg is still significantly smaller (7%) at week 52 (Petterson et al., 2011). Hence, it seems the loss of muscle CSA contributes more to the persistent muscle weakness than the deficit in muscle activation (Petterson et al., 2011).

Another less considered mechanism leading to muscle weakness is an excessive co-activation of antagonists during knee extension. In healthy conditions, co-activation of hamstrings provides stability to the knee joint (Baratta et al., 1988). However, excessive co-activation of these muscles effectively reduces the knee extension moment. Such a higher co-activation of hamstrings was found during maximum knee extensions (Stevens-Lapsley et al., 2010) and gait analyses (Benedetti et al., 2003) one and 24 month respectively after TKA. This higher co-activation, despite the loss of muscle mass, may also influence knee extension torque and movement quality (Benedetti et al., 2003).

Functional impairment in daily activities of these patients is a direct consequence of muscle weakness (Walsh et al., 1998; Mizner & Snyder-Mackler, 2005) and can even worsen with ageing (Narici & Maffulli, 2010). Sarcopenia is characterized by the loss of muscle mass and strength in old age, associated with other factors such as reduction of agonist activation (Roos et al., 1997; Häkkinen et al., 1998) and excessive co-activation (Macaluso et al., 2002). Additionally, the effects of muscle atrophy seem to worsen by concomitant changes in architectural arrangement of muscle fascicles (Narici et al., 2003). While numerous publications demonstrate the effectiveness of training to mitigate deficits related to ageing (Häkkinen et al., 1998; Harridge et al., 1999; Reeves et al., 2009), intervention studies targeting TKA patients months after surgery are scarce. Investigating the effect of aquatic training 4-18 months after TKA with a 12 months follow-up, Valtonen et al. (2010) found significant increases in leg extensor and flexor power, improvements in functional tasks and gains in thigh muscle CSA. However, all improvements but the increases in muscle power disappeared at 12 months follow-up (Valtonen et al., 2011). These results demonstrate not only the need of muscle strengthening for this population but also maintenance of an active lifestyle after TKA.

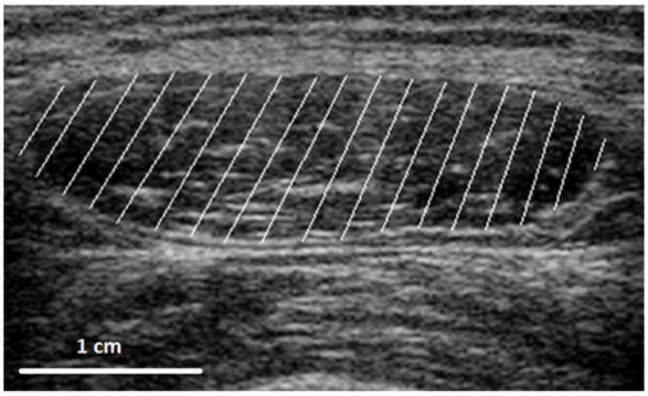
Previous publications have shown that loading of the m. quadriceps femoris during recreational skiing is an effective stimulus to increase muscle mass (Narici et al., 2011) and strength (Müller et al., 2011) in healthy older individuals. Furthermore, skiing also requires a high level of motor control for hamstring muscles. Their activation must be carefully tuned to stabilize the knee without impairing the knee extension during the turning phase (Hintermeister et al., 1995; Hintermeister et al., 1997). The optimization of co-activation patterns expected after a skiing intervention might therefore translate into a normalization of antagonist muscle coordination, via a reduction of the excessive co-activation found in TKA patients. However, a training intervention based on alpine skiing with TKA older patients has never been studied before. Therefore, the purpose of this study was to determine the effect of 12 weeks of guided skiing 2-3 times per week on knee extensor muscle architecture, strength and antagonistic co-activation 1-5 years after TKA. We hypothesized that this kind of intervention would mitigate the loss of muscle mass and strength associated with ageing and disuse and reduce excessive co-activation.

Materials and methods

Details regarding the overall study design, the patients and the skiing intervention protocol, are presented in the companion paper by Kösters et al. (2015). Briefly, 31 older adults (70.4 ± 4.7 years) with unilateral TKA, 2.7 ± 0.9 years after surgery, were assigned either to an intervention group (IG) or a control group (CG). The IG followed a guided skiing program for 12 weeks, whereas the CG did not change their daily routines over the same time span and were not allowed to ski. Muscle architectural parameters, maximum isometric knee extension and flexion torque and hamstrings co-activation were measured before and after the intervention period and after an eight week retention phase, respectively.

Muscle architecture

Muscle architecture was measured at rest with ultrasonography (LA523, 10- to 15-MHz transducer, MyLab25, Esaote, Genoa, Italy) at the beginning of each testing day. Patients were lying in a supine position while muscle scans of m. rectus femoris (RF) and m. vastus lateralis (VL) were taken from both legs at a thigh region corresponding to 40% of femur length relative to the femoral condyles (measured manually as the distance between the femoral condyles and the trochanter major). At this location, the width of the RF did not exceed that of the ultrasound field of view. All ultrasound scans were done by the same examiner. The pressure of the probe on the skin was kept to a minimum to prevent deformation of the muscles. Transparent acetate paper was used to record the location of measurements, as well as some anatomical landmarks (e.g. moles, small scars) that were used in subsequent testing sessions to ensure a consistent positioning of the template. Recordings of RF CSA, VL fascicle length (Lf), VL muscle thickness (Tm) and VL pennation angle (θ) were analyzed offline using digitizing software (ImageJ 1.41, NIH, Bethesda, USA). Fascicles were segmented manually but portions running out of the scanning frame were extrapolated as straight lines (Muraoka et al., 2001). Pennation angle was defined as the angle between the deep aponeurosis while the fascicles and muscle thickness was measured as the distance between the deep and superficial aponeuroses. An average of three measurements was obtained for each parameter for the statistical analysis. Due to the limiting range of the ultrasound probe, muscle CSA could only be measured in the RF. In VL muscle, Tm was used as a surrogate. The reliability of ultrasound based measurements of human muscle architecture and CSA has been reported in previous publications (Sipilä & Suominen, 1993; Muraoka et al., 2001).



Cross sectional area (CSA) of m. rectus femoris (RF).

Maximum voluntary contraction (MVC)

Maximum isometric torque of knee extensors and flexors was measured in a seated position on an isokinetic dynamometer (IsoMed 2000 D&R Ferstl GmbH, Hemau, Germany). The knee angle was set on 90° (180° corresponding to full extension) and patients had to perform two maximum voluntary knee extensions followed by two knee flexions with a two-minute resting period between contractions. Patients were instructed to progressively exert a torque within 3-4 seconds. The same procedure was repeated for the other leg. Afterwards, the highest MVC values were retained and normalized to body weight for further analysis. The reliability of these measurements has recently been published by Dirnberger et al. (2012).

Hamstrings co-activation

Electromyographic activity (EMG) of m. bicpes femoris (BF) was measured during isometric knee extension and flexion MVCs to quantify hamstrings co-activation. Standard procedures for skin preparation were followed (Hermens et al., 1999) before placing EMG surface electrodes (Ag/AgCL; 120 dB, input impedance: 1200 GOhm; 10 mm diameter, 22 mm spacing, Biovision, Wehrheim, Germany) over the BF. The reference electrode was placed on the lateral epicondyle of the femur. The activity of this muscle was assumed to be representative of the hamstring group (Macaluso et al., 2002). During MVCs, EMG activity of BF and torque were recorded and synchronized with a sampling frequency of 2000 Hz (biovision, Wehrheim, Germany). To process EMG data, the signal recorded during the highest MVC in each condition (knee extension and flexion) was filtered offline using a second order butterworth filter with cut off frequencies of 10 and 300 Hz. EMG activity was calculated as the root mean square (RMS) over a one-second period around peak torque. Hamstrings co-activation was determined by normalizing BF RMS during knee extension to BF RMS during knee flexion (BF RMS during knee extension / BF RMS during knee flexion; Stevens-Lapsley et al., 2010). The resulting values were multiplied by 100 afterwards to obtain percental relations.

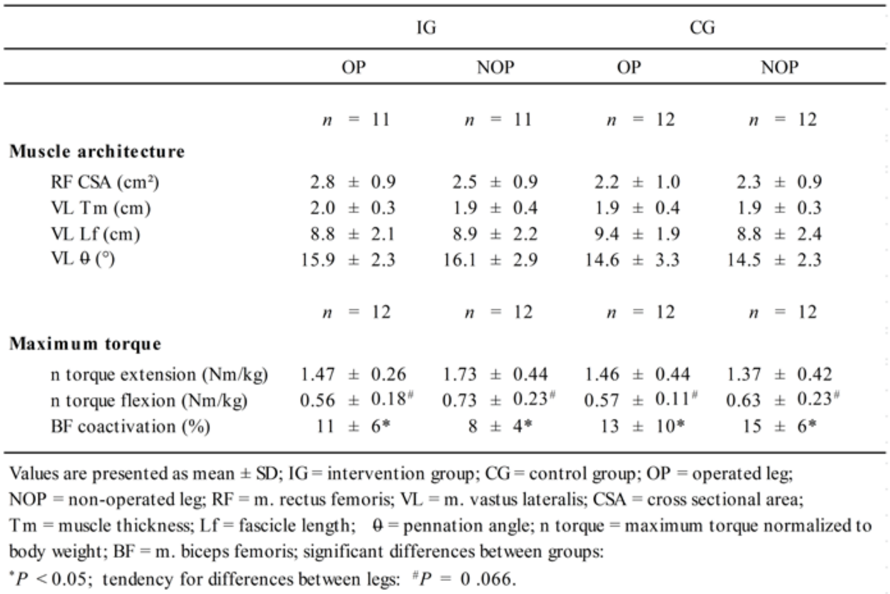
Statistics

Normality of the data distribution was tested using the Kolmogorov-Smirnov test. Baseline differences between groups and legs were assessed for each variable using a two way ANOVA with factors group (IG / CG) and leg (OP / NOP). To determine possible effects of the intervention a two way ANOVA with repeated measures of factors time (PRE / POST) x leg (OP / NOP) x group (IG / CG) was performed for each variable separately. If group x time or group x time x leg interaction effects were found to be significant further paired sample t-tests were performed as post-hoc tests for each group and leg to identify possible changes. Additionally, paired sample t-tests were calculated between post- and retention-test for each group and leg to analyze if there were any changes during the eight week retention period. Strength and co-activation data were not included in the retention-test analyses due to the reduction of the sample size at these time point and for these variables. The level of significance was set at $P < 0.05$. Data are presented as means and standard deviations (SD).

Results

Twenty-six (12 IG; 14 CG) out of the original 31 (14 IG; 17 CG) TKA patients remained after the 12-week intervention period (see Kösters et al., 2015). Data from three patients (1 IG; 2 CG) had to be excluded following the screening of ultrasound recordings due to poor image quality, while data of two other patients (CG) were refused for strength and co-activation analysis due to defective EMG signals. This reduction led to different sample sizes for muscle architecture (11 IG; 12CG) and strength/ co-activation (12 IG, 12 CG) analyses. There was a further loss of one patient (IG) for muscle and four patients (1 IG; 3 CG) for strength/ co-activation analyses from post- to retention-test. Due to the reduced sample size for strength and co-activation data, no statistical post-retention-test comparisons were performed. Baseline characteristics of the patients used in these analyses are presented in Table 1.

Baseline characteristics of patients



	IG		CG	
	OP	NOP	OP	NOP
	n = 11	n = 11	n = 12	n = 12
Muscle architecture				
RF CSA (cm²)	2.8 ± 0.9	2.5 ± 0.9	2.2 ± 1.0	2.3 ± 0.9
VL Tm (cm)	2.0 ± 0.3	1.9 ± 0.4	1.9 ± 0.4	1.9 ± 0.3
VL Lf (cm)	8.8 ± 2.1	8.9 ± 2.2	9.4 ± 1.9	8.8 ± 2.4
VL θ (°)	15.9 ± 2.3	16.1 ± 2.9	14.6 ± 3.3	14.5 ± 2.3
	n = 12	n = 12	n = 12	n = 12
Maximum torque				
n torque extension (Nm/kg)	1.47 ± 0.26	1.73 ± 0.44	1.46 ± 0.44	1.37 ± 0.42
n torque flexion (Nm/kg)	0.56 ± $0.18^{\#}$	0.73 ± $0.23^{\#}$	0.57 ± $0.11^{\#}$	0.63 ± $0.23^{\#}$
BF coactivation (%)	11 ± 6*	8 ± 4*	13 ± 10*	15 ± 6*

Values are presented as mean ± SD; IG = intervention group; CG = control group; OP = operated leg; NOP = non-operated leg; RF = m. rectus femoris; VL = m. vastus lateralis; CSA = cross sectional area; Tm = muscle thickness; Lf = fascicle length; θ = pennation angle; n torque = maximum torque normalized to body weight; BF = m. biceps femoris; significant differences between groups: $^{*}P < 0.05$; tendency for differences between legs: $^{\#}P$ = 0 .066.

Muscle architecture

There were no significant group x time x leg or group x time interactions for VL Tm, VL Lf or VL θ (all $P > 0.05$). These data are summarized in Table 2. There were also no significant group x time x leg interactions for RF CSA ($P = 0.964$; $F_{(1,21)} = 0.00$). However, the group x time interaction for RF CSA was significant ($P = 0.000$; $F_{(1,21)} = 24.06$). Post-hoc tests revealed RF CSA of the IG increased significantly in the OP (+10%; $P < 0.05$) and NOP leg (+12%; $P < 0.01$), whereas no changes occurred in the CG (Figure 2). There were no significant post-retention-test differences in any muscle variables for the two groups or legs (all $P > 0.05$).

M**.** vastus lateralis architecture at PRE-, POST- and RET-test

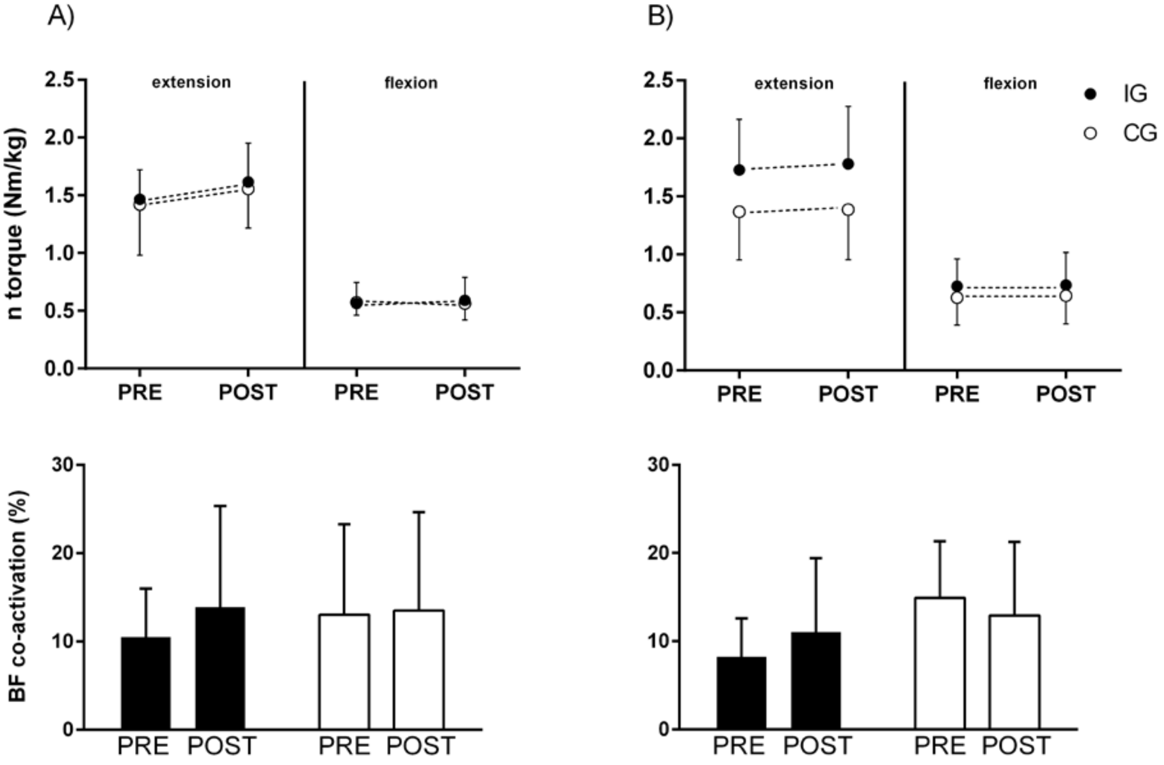
M. rectus femoris cross sectional area (CSA) at PRE-, POST- and RET-test

Maximum torque and hamstrings co-activation

There were no significant group x time x leg ($P = 0.847$; $F_{(1,22)} = 0.04$) or group x time ($P = 0.738$; $F_{(1,22)} = 0.11$) interactions for maximum knee extension torque. In addition, no significant group x time x leg ($P = 0.410$; $F_{(1,22)} = 0.706$) or group x time ($P = 0.549$;

$F_{(1,22)} = 0.37$) interactions were found for maximum knee flexion torque. Body weight did not change in the IG (85 ± 12 kg vs. 84 ± 12 kg) and CG (84 ± 15 kg vs. 83 ± 15 kg). There was no significant group x time interaction effect for this parameter (*P* = 0.882; $F_{(1,22)} = 0.23$). BF co-activation also showed no significant group x time x leg (*P* = 0.628; $F_{(1,22)} = 0.24$) or group x time (*P* = 0.160; $F_{(1,22)} = 2.11$) interactions. These data are summarized in Figure 3.

Maximum torque and m. biceps femoris (BF) co-activation at PRE- and POST-test



Discussion

The present results demonstrate the effectiveness of an alpine skiing intervention to increase muscle mass in TKA older patients, 1-5 years after surgery. After the 12-week skiing program RF CSA was significantly increased in the OP and NOP leg, although contrary to our hypothesis, the skiing intervention had no influence on VL architecture, 90° isometric strength or BF co-activation.

Muscle morphological adaptations

The skiing intervention led to a significant RF CSA gain of 10% in the OP and 12% in the NOP leg of TKA patients. These adaptations were still visible at retention-test. A hypertrophic muscle response to training, more than one year after surgery, has to date only been reported once previously in these patients (LaStayo et al., 2009). The increase in quadriceps volume (11%) observed by these authors after eccentric resistance training are in line with the results obtained in our study and are similar to quadriceps CSA increases (~10%) found in healthy older individuals after resistance training (Harridge et al., 1999; Kryger & Andersen, 2007). Although our study found a training effect for the RF only, these results reflect the resistive exercise imposed to the muscle during skiing. Downhill skiing predominantly involves eccentric work of knee extensor muscles (Berg & Eiken, 1999). Previous publications have shown eccentric loading is effective in inducing hypertrophy of type II muscle fiber and of the whole quadriceps muscles, in particular the RF muscle (Hortobágyi et al., 1996; Narici et al., 1996). Taken together, the above studies and our results suggest eccentric work induced by skiing training elicit a similar hypertrophic response in TKA patients than that obtained with resistance training in healthy elderly.

Surprisingly, we were not able to find any change in VL muscle architecture after the intervention period. This is in contrast to the findings of Narici et al. (2011) reporting increases in all architecture parameters (VL Tm: +7.1%; VL Lf: +3.4%; VL θ: +5.4%) after 12 weeks of recreational skiing in older adults. Furthermore, since eccentric tensile load seems particularly effective to increase Lf (Reeves et al., 2009), such an increase was expected with downhill skiing training. The explanation for this discrepancy is unclear but our ultrasound measurements are consistent with the lack of evidence of VL muscle hypertrophy in biopsy samples collected in the same patients (Kristensen et al., 2015). A possible explanation may be related to regional differences in muscle hypertrophy (Wells et al., 2014) and the different muscle areas that were scanned by Narici et al. (2011) and in the present protocol. Alternatively, the lack of change in VL architecture in TKA elderly could reflect different postural strategies during skiing, which would reduce the load of the VL muscle. Further investigations on these aspects are needed to investigate the influence TKA upon muscle architecture and function.

Muscle functional adaptations

Despite the RF hypertrophy, the 12-week skiing intervention had no appreciable effects on isometric torque. This result, especially for extension torque, was not expected since LaStayo et al. (2009) reported concomitant gains in quadriceps volume and in isometric extension strength in a comparable population following eccentric resistance training. Yet changes in muscle size and isometric strength are not always coupled. For instance, the hypertrophic response previously observed in healthy older individuals was accompanied by an increase in isokinetic leg press without any change in isometric knee extension torque (Müller et al., 2011). Scheiber et al.

(2012) demonstrated that a knee joint range of motion spanning 115-140° is required during recreational skiing. The lack of change in isometric torque produced at 90° may therefore be linked to the lack of specificity of this test. This explanation is further supported by results of another experiment in this same study reporting strength gains in isokinetic unilateral leg press and isometric 120° knee extension torque in the OP leg, following the intervention (Pötzelsberger et al., 2015).

Results of former publications demonstrate a persistent strength deficit in the OP leg when compared to healthy controls (Walsh et al., 1998). Recently, a skiing intervention study with healthy individuals, with a similar age to the present patients, was performed by our group (Müller et al., 2011). Using the same methodology and equipment (knee angle 90°), higher knee extension and flexion torques were measured in these subjects compared to the OP leg of our patients (1.81 Nm/kg and 0.93 Nm/kg vs. 1.47 Nm/kg 0.57 Nm/kg, respectively). However, these measurements were not performed within the same study and results have to be considered with caution. Additionally, baseline flexion torque of the OP leg tended to be weaker compared to the NOP one. These results indicate that strength deficits of lower limb muscles may exist years after TKA surgery. Accordingly, future rehabilitation/training interventions should indifferently target all major muscle groups of the lower limbs in this population.

An excessive hamstrings co-activation (~40%) has been proposed as a contributing factor to the reduction in quadriceps strength of TKA (Stevens-Lapsley et al., 2010) and healthy older individuals (Macaluso et al., 2002). However, the values (~12%) obtained in this study were lower than previously reported, without any statistical difference between legs. If high levels of hamstrings co-contractions were initially limiting knee extension torque, this problem could no longer be detected more than two years post-surgery. On the contrary, co-activation in this study was markedly lower than previously measured in healthy individuals (~20%; Macaluso et al., 2002; Stevens-Lapsley et al., 2010) and did not increase significantly after training. This discrepancy could be related to methodological differences (e.g. EMG electrodes positioning) between studies.

Perspective

Physical activity remains reduced in many TKA patients after surgery (Naal & Impellizzeri, 2010). The risk of adverse effects to which impaired muscular function and sarcopenia expose this ageing population is alarming (Narici & Maffulli, 2010). Our results showed that recreational skiing as intervention is effective in eliciting RF hypertrophy. Although no increases in isometric torque were observed at 90° of knee flexion, gains in isokinetic and isometric extension torque at 120° of knee flexion were measured and are reported in a companion paper (Pötzelsberger et al., 2015). In addition to conventional training therapies, alpine skiing appears as a feasible alternative to increase muscle mass and strength after TKA. However, VL architecture and flexion torque remained unchanged after the intervention. Further longitudinal studies with bigger samples and longer periods are needed to optimize the parameters of skiing training in this population.

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FIGURES:

Figure 1: Cross sectional area (CSA) of m. rectus femoris (RF).

Representative ultrasound image of RF CSA (white shaded area).

Figure 2: M. rectus femoris (RF) cross sectional area (CSA) at PRE-, POST- and RET-test.

RF CSA at PRE-, POST- and RET-test in the intervention group (IG: black) and the control group (CG: white) for the A) operated and B) non-operated leg. Significant group x time interaction $P < 0.01$. . Significant differences from PRE- to POST-test: *$P < 0.05$; **$P < 0.01$.

Figure 3: Maximum torque and m. biceps femoris (BF) co-activation at PRE- and POST-test.

Maximum normalized torque and BF co-activation at PRE- and POST-test in the intervention group (IG: black) and control group (CG: white) for A) the operated and B) non-operated leg.