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Alpine Skiing With total knee ArthroPlasty (ASWAP): Effect on Tendon Properties.

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Abstract

The aim of this study was to investigate the effect of alpine skiing on patellar tendon properties in patients with total knee arthroplasty (TKA). Thirty-one adults (70.4 ± 4.7 years) with unilateral TKA were recruited 2.7 ± 0.9 years after surgery and assigned to an intervention (IG) or a control group (CG). The IG underwent a 12-week guided skiing program (Kösters et al., 2015). Tendon stiffness, Young's modulus and cross-sectional area (CSA) were measured before and after the intervention. In both groups, mean tendon CSA was 28% ($P < 0.001$) larger in the operated (OP) than in the non-operated (NOP) leg at baseline, without any difference in other tendon properties. After training, stiffness increased in the IG by 5.8% and 15.8%, respectively, in the OP and NOP legs. Likewise, mean CSA increased in the IG by 2.9% in the OP and 3.8% in the NOP leg, whereas no significant changes were found for the Young´s modulus. None of the tendon parameters changed in the CG. Results indicate that patellar tendon structure and/or loading pattern are altered following TKA, but this tissue seems to retain its adaptation capacity. Further, alpine skiing appears to offer a suitable rehabilitation strategie for TKA patients.

Introduction

Deficits in knee extensor moment are well documented after total knee arthroplasty (TKA) (Mizner et al., 2005; Vissers et al., 2013). Quadriceps muscle strength and associated functional abilities like walking or stair climbing often fail to reach previous levels, even after several years post-surgery (Meier et al., 2008; Valtonen et al., 2009; Stevens-Lapsley et al., 2010). Beside muscle mass and neuromuscular activation, the generated knee extensor moment of TKA patients seems affected by two main factors: the force-ratio between the quadriceps and the patellar tendon (Browne et al., 2005; Ward et al., 2012) and the patellar tendon moment arm. The ratio between quadriceps tendon force and patellar tendon force defines how quadriceps force is transmitted to the patella tendon and is determined by the geometrical arrangement of the patella, the patellar and quadriceps tendons and by the patella-femoral articulation. Hence, the alterations in knee geometry (Ho et al., 2012; Clary et al., 2013) and extensor moment arms stemming from TKA are expected to influence force transmission between the quadriceps muscles and the patellar tendon (Ward et al., 2012). For instance, Gejo et al. (2009) reported such alterations, measured via intraoperative patellar tendon strain at 60°, 90° and 135° of flexion, to affect postoperative range of motion.

Tendon is a metabolically active structure (Bojsen-Møller et al., 2006) displaying adaptive responses to alterations in mechanical loading (Kjaer et al., 2009). Accordingly, training (Arampatzis et al., 2007; Kongsgaard et al., 2007; Kubo et al., 2001; Reeves et al., 2003) and disuse (de Boer et al., 2007) studies have shown changes in tendon morphological, mechanical and material properties. It follows that changes in tendon mechanical loading observed in TKA patients (Stagni et al., 2010; Akkawi et al., 2014) may require such adaptations (Galloway et al., 2013) to prevent injury and/or to maintain functional capacity. . However, morphological and material adjustments following TKA and/or exercise training are currently undocumented in these patients. The Load imposed upon the quadriceps muscles during recreational alpine skiing is associated with a sustained strain of the patellar tendon.

By loading the knee joint without impact, at an intensity equating to about one body weight on the outer leg during a ski turn (Scheiber et al., 2012), skiing arguably constitutes an entertaining, suitable alternative to train TKA patients. This form of training has indeed been shown to safely increase quadriceps strength in healthy older subjects, with concomitant increases in patellar tendon stiffness (+14%) and Young´s modulus (+12%) after 12 weeks (Seynnes et al., 2011).

The aim of the present study was to examine side-to-side differences in patellar tendon properties of TKA patients and to investigate the responsiveness of this tendon in the operated (OP) side following a program of supervised alpine skiing. We hypothesised that the OP side would display a reduced tendon stiffness stemming from strength impairments, when compared to the non-operated (NOP) side. We also expected that the large amount of patellar tendon strain required during skiing would result in a substantial increase in tendon stiffness in both sides, which would mitigate side-to-side differences.

Materials and methods

The detailed study design, the intervention protocol and the patient recruitment are presented in the companion paper by Kösters et al. (2015). In brief, 31 older adults (70.4 ± 4.7 years) with unilateral TKA were recruited 2.7 ± 0.9 years after surgery and assigned to an intervention (IG) or a control group (CG). The intervention consisted in a 12-week guided skiing program, 2-3 times/week, 3.5 h/session, while subjects of the CG did not change their daily routines but were not allowed to ski.

Tendon morphology

Patients were seated on an isokinetic dynamometer (IsoMed 2000 D&R Ferstl GmbH, Hemau, Germany) with a knee angle of 90° (0° corresponding to full extension) and strapped with safety belts. Ultrasound recordings (LA523, 10-to15-MHz transducer, MyLab25, Esaote, Genoa, Italy) of patellar tendon length and cross sectional area (CSA) were performed on both sides (Figure 1), in the longitudinal and transversal plane, respectively. Patellar tendon length was defined as the distance between the tibial insertion and the apex of the patella and CSA was measured proximally (CSAp), below the apex of the patella, at mid-length (CSAm) and distally (CSAd), above the tibial insertion. Mean tendon CSA was obtained by averaging CSAp, CSAm and CSAd. Tendon CSA and length were analyzed offline using a digitizing software (ImageJ1.41, NIH, Bethesda, USA).

Tendon mechanical properties

To determine tendon strain, stiffness and Young´s modulus, the patellar tendon elongation during maximal isometric ramp contractions was recorded using ultrasonography. Tendon elongation was measured offline as the displacement of the patellar apex relative to the tibial plateau, using software for semi-automated tracking (Tracker 4.8, Cabrillo.edu/-dbrown/tracker). After 3 submaximal familiarization trials, patients were asked to perform 3 isometric contractions at a constant loading rate (110 Nm/s) with the help of visual feedback. The control of loading rate was required to ensure consistency between trials and between subjects (Kösters et al., 2014). Torque signals were synchronized with ultrasound recordings and m. biceps femoris (BF) electromyographic activity (EMG). To record EMG, surface electrodes (Ag/AgCL; 120 dB, Input impedance: 1200 GOhm; 10 mm diameter, 22 mm spacing, Biovision, Wehrheim, Germany) were placed over the belly of the BF muscle and one reference electrode placed on the lateral epicondyle of the femur (Hermens et al., 2000). Activity of the BF muscle during maximum voluntary knee flexion was recorded and filtered offline using a second order butterworth filter with cut off frequencies of 10 and 300 Hz. The ratio between peak torque and EMG root mean square (0.5s around peak torque) was calculated and multiplied by the knee extension torque to obtain the net extension torque, assuming a linear relation between EMG activity and torque. Patellar tendon force was calculated by dividing the net extension torque by the tendon moment arm length, estimated individually from normative data via femur length (Visser et al., 1990).

Tendon force- elongation relationships were plotted and fitted with a second order polynomial function. Stiffness and Young´s modulus were calculated for each relationship over the highest 10% interval of individual force using: Eq. (1) and Eq. (2).

$$\mathrm{k} = \frac{\Delta \mathrm{F}}{\Delta \mathrm{l}} \qquad \text{Eq. 1}$$

$$\mathrm{E} = \mathrm{k} \times \frac{\mathrm{lo}}{\mathrm{CSA}} \qquad \text{Eq. 2}$$

Where ΔF is the change in force and Δl describes the tendon deformation over the force interval. CSA is the mean tendon cross sectional area and lo is the resting tendon length. Tendon strain was calculated as the maximal tendon elongation in relation to its resting length. Force-elongation relations presenting a coefficient of determination R^2 superior to 0.90 were retained and averaged for further analysis. For possible measurement errors and reliability of the method see Kösters et al. (2014).

Statistics

After confirming normality of data distribution (Kolmogorov-Smirnov test), baseline differences between groups and legs were assessed using a two way ANOVA with factors group (IG / CG) and leg (OP / NOP). Possible effects of the intervention were determined by a three way ANOVA with repeated measures for factors time (PRE / POST), leg (OP / NOP) and group (IG / CG).

SPSS 22 for Windows was used for all anlaysis. The level of significance was set at $P < 0.05$. Data are presented as means and standard deviations (SD).

Results

The data from three patients (1 IG; 2 CG) had to be excluded following the screening of ultrasound recordings due to an insufficient image quality and because of missing EMG recordings for one patient (1 CG). Therefore, 27 (13 IG; 14 CG) out of the original 31 (14 IG; 17 CG) TKA patients remained in the data set for tendon analysis.

No differences in age, weight, height, BMI and year after operation at baseline were observed between IG (4 ♀; 9 ♂) and CG (5 ♀; 9 ♂) (Table 1).

Baseline values of extension torque normalized to bodyweight (n torque), stiffness, Young´s modulus and mean CSA values are presented in Table 2. A significant leg effect (P<0.001; $F_{(1,48)}$=18.33) was observed for mean CSA, supporting the larger values measured in the OP versus NOP leg for both groups (+28% on average). A significant leg effect (CSAp, P = 0.0039; CSAm, P < 0.0001; CSAd, P = 0.013) indicated baseline differences between OP and NOP in all measured sites (Figure 2).

The analysis of the post-intervention differences revealed a significant time x group interaction for stiffness, supporting the 5.6% and 15.8% increases observed in this parameter in the OP and NOP legs, respectively (Figure 3A, Table 3). Likewise a time x group interaction was found for mean tendon CSA, indicating that mean CSA increased by 2.9% in the OP and 3.8% in the NOP leg (Figure 3B, Table 3). However, no significant differences were detected for the Young´s modulus (IG post OP: 0.63 (SD 0.34) GPa; IG post NOP: 0.78 (SD 0.27) GPa; CG post OP: 0.63 (SD 0.17) GPa; CG post NOP: 0.66 (SD 0.26) GPa).

Along the tendon length, a time x group interaction was found for CSAp and CSAm, but not for CSAd, indicating that tendon hypertrophy occurred proximally and tendon mid-region in the IG (Table 4). In the IG, CSAp increased by 5.9% in the OP leg and by 8.0% in NOP leg, and CSAm increased by 2.0% and 1.1% in the OP and NOP legs, respectively (Figure 4, Table 4).The lack of significant time x leg or time x group x leg interaction effects for any of the measured variables reflects the lack of statistical differences between the changes observed in the OP or the NOP leg.

Discussion

The aim of the present study was to evaluate the morphological and mechanical properties of the patellar tendon in TKA patients and to investigate the adaptive responses of this tissue after an alpine skiing intervention. Our results indicate that (i) patellar tendon CSA is larger in the OP leg than in the NOP leg at baseline and, (ii) a 12-week skiing intervention induces an increase in tensile stiffness and CSA of this tendon.

Patellar tendon properties in TKA patients

Several years (2.7 ± 0.9 years) after TKA, no differences in isometric knee extensor strength could be observed between OP and NOP leg of patients tested in the present conditions (Table 2). Accordingly, mechanical and material properties measured as tensile stiffness and Young´s modulus, respectively, did not appreciably differ between legs at baseline. Yet the 28% larger tendon CSA measured in the OP leg is remarkable. Comparable differences in patellar tendon CSA have previously been observed after years of physical training (Couppé et al., 2008; Seynnes et al., 2013) but these were typically paralleled by differences in stiffness. Interestingly, larger (21%) CSA values without difference in stiffness have also been found in orthopaedic patients, years after a graft was harvested from their patellar tendon (Reeves et al., 2009). However, in the case of these patients, the authors also found a reduced Young’s modulus and advocated the proliferation of scar tissue with inferior mechanical properties as a compensatory mechanism. A typical TKA necessitates procedures such as a resection of parts of the femoral and tibial plateau to correct for varus-valgus malposition and sometimes, patellar resurfacing; but, it does not commonly require severing the patellar tendon. However, damage to the collagenous structure of the patellar tendon may occur during TKA and scar tissue proliferation may constitute a mechanism that promotes hypertrophy. Alternatively, enlargement of the tendon may indirectly result from profound modifications in knee joint geometry (Bull et al., 2008; Ho et al., 2012; Watanabe et al., 2014) and tendon loading associated with TKA. For instance, elevated knee extension power was found following lengthening of the patellar tendon moment arm, due to a posterior shift of the joint centre of rotation in single radius implant designs (Mahoney et al., 2002; Hamilton et al., 2013). Furthermore, the resection of the infrapatellar fatpad performed during TKA is associated with a decrease in patellar tendon length (Lemon et al., 2007; Van Beeck et al., 2013), thereby altering the tendon orientation (defined as the angle between the patellar tendon and the posterior border of the tibia) and patellofemoral contact force. In line with this, Ward et al. (2012) showed an increase of about 3% in patellofemoral force when increasing the patellar tendon angle by only 1° *in vitro*. Taken together, alterations stemming from TKA procedures likely affect magnitude and nature of the stress imposed upon the patellar tendon. Hypothetically, hypertrophy may constitute an adaptive response required to shield the tendon structure, which was optimised during growth for the original knee geometry and loading pattern of the patient. Interestingly, if this mechanism explains the larger tendon observed in TKA patients, the larger CSA measured in all sites of the OP side suggests that stress changes elicited by the surgical procedures uniformly affected the tendon. The mechanisms leading to changes in tendon morphological and material properties are still poorly understood. Owing to the physical link between material CSA and stiffness, the present lack of side-to-side differences in tendon Young's modulus does not fit with similar stiffness found in hypertrophied tendons. The reasons for this discrepancy are unknown but our analysis may have been limited by our methodological approach. Indeed, the normative data used to estimate moment arm length from femur length measurements were collected in healthy subjects (Visser et al., 1990) and may be inappropriate for TKA patients because of the aforementioned joint alterations. Future studies should address this limitation by including more direct measures of each patellar tendon moment arm.

Alpine skiing intervention

Despite the important modifications associated with TKA procedures, the present study also shows that the patellar tendon retains the capacity to alter its properties in response to increased loading. The metabolic responsiveness of tendon to loading alterations has been shown to elicit an elevated collagen synthesis after training (Langberg et al., 2001; Miller et al., 2005), which may be mediated by the expression of certain growth factors (see Heinemeier and Kjaer, 2011 for review). This increase in collagen production is in turn believed to support the changes in tendon properties typically observed with increased loading (Kubo et al., 2001; Kongsgaard et al., 2007; Seynnes et al., 2009). Tensile stiffness and CSA were increased in OP and NOP legs after the present intervention. This suggests an adaptive response to mechanical stress induced by alpine skiing. The tendon stiffening found in TKA patients is congruous with a previous study in healthy older subjects (Seynnes et al., 2011), showing a 14% increase in this parameter after a comparable skiing intervention. However, in the study by Seynnes and colleagues (2011), this increase was associated with an increase in Young's modulus, without any significant change in tendon CSA, whereas we observed tendon hypertrophy and unchanged material properties. The reasons for this discrepancy are not known but the magnitude of the changes in tendon mean CSA in TKA patients (+4.8%) is close to the non significant increase (+3.4%, $P = 0.24$) reported in healthy individuals. Albeit speculative, a type II error may have occurred in the latter case because of an insufficient measurement resolution. Such an error would mathematically reconcile findings from both studies regarding the relative contribution of hypertrophy and modulus to changes in stiffness. An increase in CSA has previously been observed near the insertion sites of the patellar tendon following heavy resistance training (Kongsgaard et al., 2007, Seynnes 2009) and is thought to be mediated by the combined tensile and compressive stresses in these regions. However, the pattern of hypertrophic response to training seems different in TKA patients. As evidenced by the larger CSA observed in the proximal and middle regions (7%, $P < 0.001$ and 1.5%, $P = 0.02$ respectively) and by a similar trend distally (2.8%, $P = 0.08$), tendon morphological changes also affected non-insertional areas. However, the lack of significant time x group x leg effect suggests that the more uniform tendon hypertrophy measured here may have occurred because of factors related to training or individual physical status, rather than TKA. A noteworthy aspect of the adaptations observed in TKA patients is the apparent differences in tendon stiffening and hypertrophy between the OP and NOP legs. Stiffness and mean CSA increased by 5.6% and 2.9%, respectively, in the OP leg and by 15.8% and 3.8%, respectively, in the NOP leg. These findings suggest a reduced adaptive capacity of the patellar tendon after TKA, potentially due to scar tissue proliferation and changes in the proportion of healthy tissue. However, smaller adaptations may also have been caused by modifications in knee loading pattern mentioned above or by an unconscious tendency of TKA patients to preferably load the NOP leg. None of these potential mechanisms can be inferred from the present results and future studies should be designed to investigate each of these aspects.

Perspective

Increased life expectancy and recourse to TKA among younger adults imply that more patients will live with a total knee replacement for a longer time. Tendon integrity and adaptive capability are essential features of a successful rehabilitation and return to previous levels of functional capacity and lifestyle. The hypertrophied patellar tendons observed in the OP leg of TKA patients indicate procedures may still be improved to minimize the damage caused to this structure during surgery. Changes in tendon properties found in both legs following recreational alpine skiing demonstrates that this activity constitutes an interesting alternative to typical exercise routines proposed to TKA patients.

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Table 1: Patients demographics (mean ±SD)

	IG			CG		
	female	male	all	female	male	all
n	4	9	13	5	9	14
age (years)	66.2 ± 3.7	71.4 ± 2.9	69.8 ± 4.1	67.5 ± 5.5	73.4 ± 4.0	71.3 ± 5.4
weight (kg)	79.8 ± 11.8	86.5 ± 10.7	84.4 ± 11.8	78.1 ± 16.9	89.8 ± 12.4	85.6 ± 14.7
height (cm)	159.7 ± 10.5	175.8 ± 4.1	170.9 ± 10.1	163.0 ± 9.4	169.6 ± 6.3	167.2 ± 7.9
post operation (years)	2.5 ± 1.1	2.6 ± 1.1	2.6 ± 1.0	3.3 ± 0.7	2.1 ± 0.6	2.6 ± 0.8

IG: intervention group; CG: control group

Table 2: Mean (± SD) Baseline values of stiffness, Young´s modulus and cross-sectional area (CSA)

	n torque [Nm/kg]		Stiffness [N/mm]		Young´s Modulus [Gpa]		CSA [mm^2]	
	OP	*NOP*	*OP*	*NOP*	*OP*	*NOP*	*OP*	*NOP*
IG	1.57 ± 0.34	1.80 ± 0.52	2401 ± 1194	2036 ± 559	0.67 ± 0.47	0.72 ± 0.19	173 ± 41	130 ± 11
CG	1.56 ± 0.36	1.56 ± 0.54	2082 ± 635	1809 ± 631	0.62 ± 0.19	0.70 ± 0.25	155 ± 32	126 ± 30
Effects / Interaction	-		-		-		a	

IG: intervention group; CG: control group; OP: operated leg; NOP: non operated leg;

a: P<0.001 leg effect in a 2 (IG, CG) x 2 (OP, NOP) analysis of variance.

Table 3: 3 x 2 analyses of variance with repeated measures for stiffness, Young´s modulus and mean cross-sectional area (CSAmean)

	Stiffness [N/mm] IG (13), CG (14), df 1, 48			Young´s Modulus [GPa] IG (13), CG (14), df 1, 48			CSAmean [mm^2] IG (13), CG (14), df 1, 48		
	F	η^2	*P*	F	η^2	*P*	F	η^2	*P*
Time effect	3.59	0.07	0.06	0.00	0.00	0.99	8.32	0.15	<0.01 **
Group effect	3.77	0.07	0.06	0.38	0.01	0.54	2.77	0.06	0.10
Leg effect	1.92	0.04	0.17	1.07	0.02	0.31	18.83	0.28	<0.001 ***
Interaction time x group	6.18	0.11	0.02 *	0.27	0.00	0.61	20.63	0.30	<0.001 ***
Interaction time x leg	0.38	0.01	0.54	0.33	0.00	0.57	0.26	0.00	0.61
Interaction time x group x leg	1.40	0.03	0.24	3.24	0.06	0.08	0.68	0.01	0.41

IG: intervention group; CG: control group; time (pre/post), group (IG/CG) and leg (OP/NOP) factors were included in the analysis; * P < 0.05; ** P < 0.01; *** P < 0.001

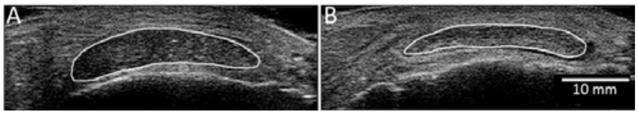
Table 4: 3 x 2 analyses of variance with repeated measures for proximal, mid-length and distal cross sectional area (CSAp, CSAm and CSAd)

	CSA p [mm^2] IG (13), CG (14), df 1, 48			CSA m [mm^2] IG (13), CG (14), df 1, 48			CSA d [mm^2] IG (13), CG (14), df 1, 48		
	F	η^2	*P*	F	η^2	*P*	F	η^2	*P*
Time effect	13.68	0.23	<0.01 **	0.01	0.00	0.93	5.69	0.11	0.02 *
Group effect	0.78	0.02	0.38	1.89	0.03	0.21	3.63	0.07	0.06
Leg effect	11.89	0.21	<0.01 **	24.41	0.35	<0.001 ***	7.36	0.14	<0.01 **
Interaction time x group	24.14	0.34	<0.001 ***	5.76	0.11	0.02 *	3.18	0.07	0.08
Interaction time x leg	0.39	0.01	0.54	2.45	0.05	0.12	1.69	0.04	0.20
Interaction time x group x leg	0.36	0.01	0.55	0.26	0.01	0.61	0.55	0.01	0.46

IG: intervention group; CG: control group; time (pre/post), group (IG/CG) and leg (OP/NOP) factors were included in the analysis; * P < 0.05; ** P < 0.01; *** P < 0.001

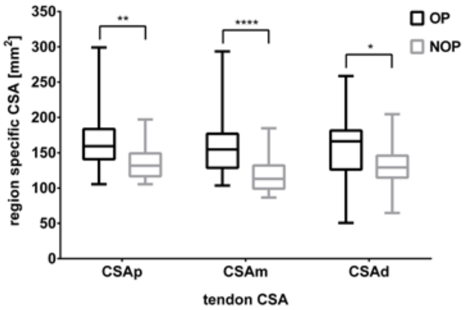
Figures

Figure 1: Patellar tendon cross sectional area (CSA)



Representative ultrasound image of the patellar tendon cross sectional area (CSA) in the operated side (A) and the non-operated side (B)

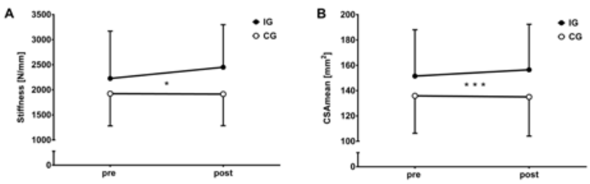
Figure 2: Region specific patellar tendon cross sectional area (CSA)



Baseline differences in tendon CSA between legs (OP/NOP) at different tendon regions – proximal (CSAp), mid-length (CSAm) and distal (CSAd). Pooled data from the intervention and control groups.

* P<0.05; ** P<0.01; ****P<0.0001

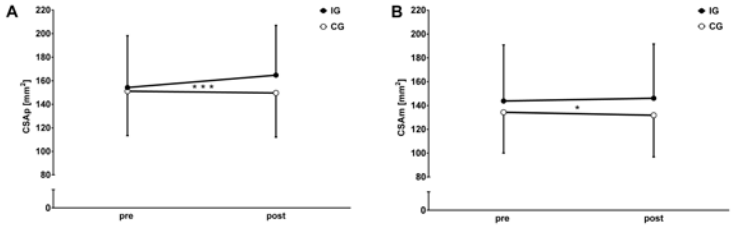
Figure 3: Changes in stiffness and mean cross sectional area (CSAmean) of the patellar tendon



Stiffness (A) and CSAmean (B) values for the Intervention (IG) and Control (CG) groups before (pre) and after (post) the skiing intervention

# P<0.05; # # # P<0.001 levels for time x group interaction

Figure 4: Changes in proximaland mid-lengthcross sectional area (CSAp, CSAm) of the patellar tendon



Proximal (A) and mid-length CSAm (B) values for the Intervention (IG) and Control (CG) groups before (pre) and after (post) the skiing intervention

# P<0.05; # # # P<0.001 levels for time x group interaction