



# Patellar Tendon Shear Wave Velocity Is Higher and has Different Regional Patterns in Elite Competitive Alpine Skiers than in Healthy Controls

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Competitive alpine skiers are exposed to enormous forces acting on their bodies—particularly on the knee joint and hence the patellar tendon - during both the off-season preparation and in-season competition phases. However, factors influencing patellar tendon adaptation and regional pattern differences between alpine skiers and healthy controls are not yet fully understood, but are essential for deriving effective screening approaches and preventative countermeasures. Thirty elite competitive alpine skiers, all members of the Swiss Alpine Ski Team, and 38 healthy age-matched controls were recruited. A set of two-dimensional shear wave elastography measurements of the PT was acquired and projected into three-dimensional space yielding a volumetric representation of the shear wave velocity profile of the patellar tendon. Multivariate linear models served to quantify differences between the two cohorts and effects of other confounding variables with respect to regional shear wave velocity. A significant ( $p < 0.001$ ) intergroup difference was found between skiers (mean  $\pm$  SD = 10.4  $\pm$  1.32 m/s) and controls (mean  $\pm$  SD = 8.9  $\pm$  1.59 m/s). A significant sex difference was found within skiers ( $p = 0.024$ ), but no such difference was found in the control group ( $p = 0.842$ ). Regional SWV pattern alterations between skiers and controls were found for the distal region when compared to the mid-portion ( $p = 0.023$ ). Competitive alpine skiers exhibit higher SWV in all PT regions than healthy controls, potentially caused by long-term adaptations to heavy tendon loading. The presence of sex-specific differences in PT SWV in skiers but not in controls indicates that sex effects have load-dependent dimensions. Alterations in regional SWV patterns between skiers and controls suggest that patellar tendon adaptation is region specific. In addition to the implementation of 3D SWE, deeper insights into long-term tendon adaptation and normative values for the purpose of preventative screening are provided.

**Keywords:** knee, tendinopathy, shear wave elastography, injury prevention, athletes, alpine ski racing

## 1 INTRODUCTION

Tendons transmit the forces from muscles to the skeleton and are thus crucial for human locomotion. Similar to other connective tissues, tendons are able to respond to various intrinsic and extrinsic stimuli through morphological and material property adaptations. Among others, tendon loading, age (Carroll et al., 2008; Hsiao et al., 2015), sex (Magnusson et al., 2007), body mass index (BMI) (Gumina et al., 2014) and nutritional habits (Scott et al., 2015; Korntner et al., 2017) are factors influencing tendon properties.

Repetitive exertion of tensile stress on tendons can promote tendon remodeling and thickening (Bohm et al., 2015), involving both collagen synthesis and degradation (Magnusson et al., 2010). Additionally, upregulated enzymatic cross-linking increases the structural integrity of the tissue (Svensson et al., 2016; Passini et al., 2021). Repetitive excessive overloading and inadequate repair mechanisms can, however, induce cumulated tendon damage and trigger degenerative pathological processes (Cook and Purdam, 2009), including an increase in collagen type III fibers, fibrocartilaginous changes through the decomposition of glycosaminoglycans (GAGs), neovascularization and tenocyte rounding and proliferation (Maffulli et al., 2000; Fredberg and Stengaard-Pedersen, 2008; Attia et al., 2014; Snedeker and Foolen, 2017). Compared to collagen type I fibers, collagen type III fibers exhibit a reduced ability to form cross-links, thus decreasing fiber orientation and mechanical strength within the tendon (Maffulli et al., 2000). GAGs contain highly hydrophilic side chains and therefore increase the water content within the tendon. These degenerative adaptations deteriorate the mechanical properties of the pathologic tendons (Seo et al., 2015; Ooi et al., 2016; Finnamore et al., 2019) and favor traumatic tendon injuries (Cook and Purdam, 2009; Yasui et al., 2017). From a screening and injury prevention perspective, however, both physiological and pathological processes are crucial since tendon pathologies move along a partially reversible continuum (Cook and Purdam, 2009).

Physiological adaptations contribute to athletic performance (energy storage-releasing capacity of tendon) (McGuigan et al., 2006; Van Hooren and Zolotarjova, 2017; Groeber et al., 2021), whereas pathological developments can jeopardize an athletic career (Kettunen et al., 2002; Lian et al., 2005; Zwerver et al., 2011). Transferring the forces exerted by *M. quadriceps femoris* from the lateral apex of the patella to the tibial tuberosity and, hence, being involved in many daily and sports-related activities, the patellar tendon (PT) bears high volumes of heavy loads. Substantial differences in morphological and mechanical PT properties between team sports athletes (i.e., Volleyball and basketball players) and the general population were reported (Zhang et al., 2015; Bayliss et al., 2016). In particular, high magnitude loading, such as exercising close to the maximal strength capacities, induced significant tendon adaptation (Malliaras et al., 2013; Bohm et al., 2015).

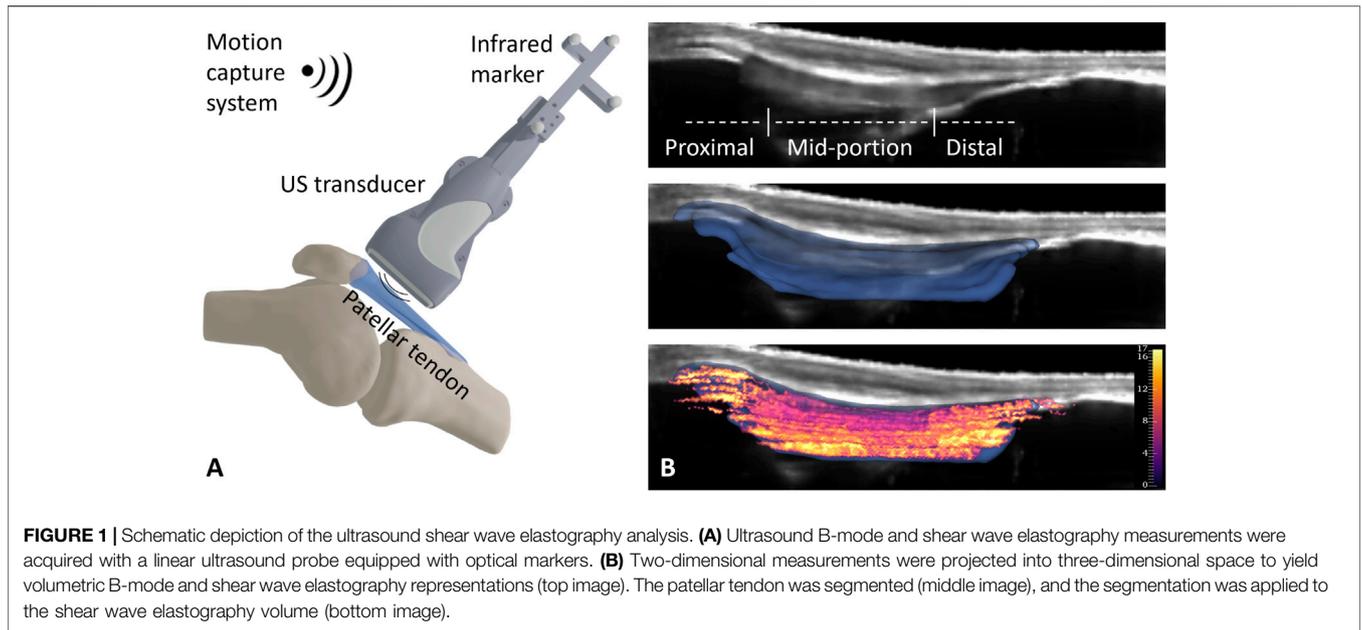
One cohort exposed to high PT loads during both the off-season preparation and in-season competition phases are competitive alpine skiers. During the preparation phase,

plyometric and heavy weight exercises are frequently performed, both exerting large loads on the PT (Hydren et al., 2013). On-snow training and competition can require skiers to perform 33,000 turns per season, whereby the ground reaction force peaks at up to 4 times body weight (Supej and Holmberg, 2010; Gilgien et al., 2018). These forces act—due to the constantly flexed knee position—strongly on the knee extensor muscle-tendon unit and, thus, the PT (Alhammoud et al., 2020). Therefore, healthy competitive alpine skiers are considered a suitable cohort for the detection of physiological PT adaptations. However, it is not yet clear whether differences in tendon adaptation can be observed between competitive alpine skiers and healthy controls and to what extent other factors act on tendon properties within the two groups.

Ultrasound (US) shear wave elastography allows on-site assessment of tissue mechanical properties. A focused acoustic radiation impulse induces tissue displacement that propagates perpendicularly to the direction of the impulse and can be observed with high frame rate (3–18 kHz) brightness mode (B-mode) US and appropriate tracking algorithms (Hein and O'Brien, 1993). The instantaneous group shear wave velocity (SWV) can be mapped on a regular grid superimposed onto the B-mode US image and is related to the tissues' elastic properties (Nightingale, 2011). In detecting pathological and traumatic conditions of musculoskeletal structures, the quantitative assessment of elastic properties has proven valuable (Taljanovic et al., 2017). Particularly in depicting tendon damage and degeneration as well as predicting impending structural failure, shear wave elastography (SWE) shows great potential (Aubry et al., 2015).

Tissue property assessments using US SWE are commonly performed in a two-dimensional (2D) manner. In particular, the investigation of larger structures is impeded by the limited field of view (FOV); therefore, the results are highly position dependent. In particular, tendon imaging requires accurate spatial referencing, as pathological characteristics in structural composition and architecture are typically spatially confined (Johnson et al., 1996; Khan et al., 1996; Pearson and Hussain, 2014). To overcome these limitations, we have previously implemented and validated an approach for three-dimensional US shear wave velocity mapping (Götschi et al., 2021). The technique allows sampling of larger structures primarily limited by the maximum measurement depth of the system and enables off-line analysis of distinct subregions (Götschi et al., 2021).

Based on this background, the current study was undertaken to 1) investigate differences in PT SWV in competitive alpine skiers compared to age-matched healthy control subjects, to 2) evaluate sex-specific differences in PT SWV, and to 3) describe potential differences in regional SWV patterns in both cohorts. Considering the literature and the high training volumes and loads in competitive alpine skiers, an increased SWV in the skier cohort compared to the control group was hypothesized. For the reasons stated above, it was also expected that the PT of male subjects would have a higher SWV than that of female subjects.



**TABLE 1** | Baseline characteristics.

Parameter	Control Group (n = 38, female: 20)	Skier Group (n = 30, female: 14)	Overall (n = 68, female: 34)	p value	
Age [years]	24.9 ± 2.50	23.6 ± 2.50	24.4 ± 2.57	0.982	ns
Weight [kg]	65.9 ± 10.3	73.7 ± 10.7	69.3 ± 11.1	0.002	**
Height [cm]	172 ± 8.71	173 ± 9.37	172 ± 8.95	0.324	ns
BMI [kg/m <sup>2</sup> ]	22.2 ± 2.18	24.5 ± 1.81	23.2 ± 2.32	<0.001	**

Data are expressed as the mean ± SD (\*\*): p < 0.01 (ns): p > 0.05.

**TABLE 2** | Inference models identified group membership as the only significant predictor for shear wave velocity of the entire study population in all assessed tendon regions.

Tendon region	Predictor	Estimate [ms <sup>-1</sup> ]	Std-Error [ms <sup>-1</sup> ]	p value	
Overall	Skier group	1.495	0.328	< 0.001	**
	Sex	0.263	0.325	0.422	ns
Proximal	Skier group	1.184	0.357	0.002	**
	Sex	0.116	0.366	0.753	ns
	Tendon length	0.054	0.028	0.061	ns
Mid-portion	Skier group	1.401	0.359	< 0.001	**
	Sex	0.256	0.365	0.486	ns
	Tendon length	0.045	0.028	0.117	ns
Distal	Skier group	2.202	0.447	< 0.001	**
	Sex	0.023	0.443	0.959	ns

(\*\*): p < 0.01, (ns): p > 0.05.

## MATERIALS AND METHODS

### Participants and Study Design

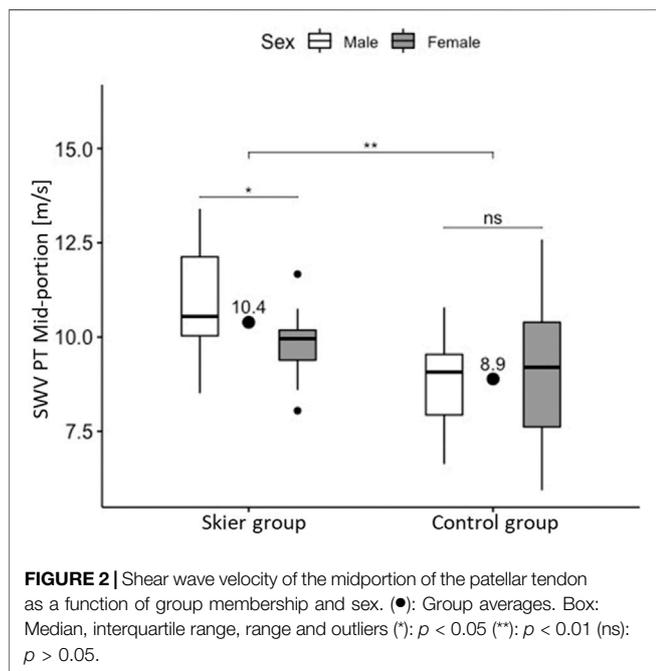
Thirty-nine elite competitive alpine skiers (skier group), all members of the Swiss Alpine Ski Team, and 38 age-matched healthy controls were recruited for the conduction of this case-control study. In winter, i.e., during the competition

period, the training of elite competitive alpine skiers typically includes 1 to 3 on-snow competitions and/or on-snow training sessions, as well as 7 to 14 off-snow training sessions per week (Gilgien et al., 2018). In summer, i.e., during the off-season training period, they train an average of 5–9 sessions on-snow and 6 to 18 sessions off-snow per week, resulting in a total of 14–21 h of training per week (Gilgien et al., 2018). During the first

**TABLE 3** | Predictive factors of shear wave velocity in the skier group. In the control group, no predictive factors were identified.

Target	Predictor	Estimate	Std- error	p value	
Skier Group	Proximal				
	Male sex	0.927 ms <sup>-1</sup>	0.524 ms <sup>-1</sup>	0.088	ns
	Tendon length	0.058	0.034	0.102	ns
Mid-portion	BMI	-0.212	0.141	0.144	ns
	Age	-0.172 ms <sup>-1</sup> year <sup>-1</sup>	0.087 ms <sup>-1</sup> year <sup>-1</sup>	0.057	ns
Distal	Male sex	1.080 ms <sup>-1</sup>	0.428 ms <sup>-1</sup>	0.018	*
	Male sex	0.035 ms <sup>-1</sup>	0.678 ms <sup>-1</sup>	0.960	ns

(\*):  $p < 0.05$ , (ns):  $p > 0.05$ .

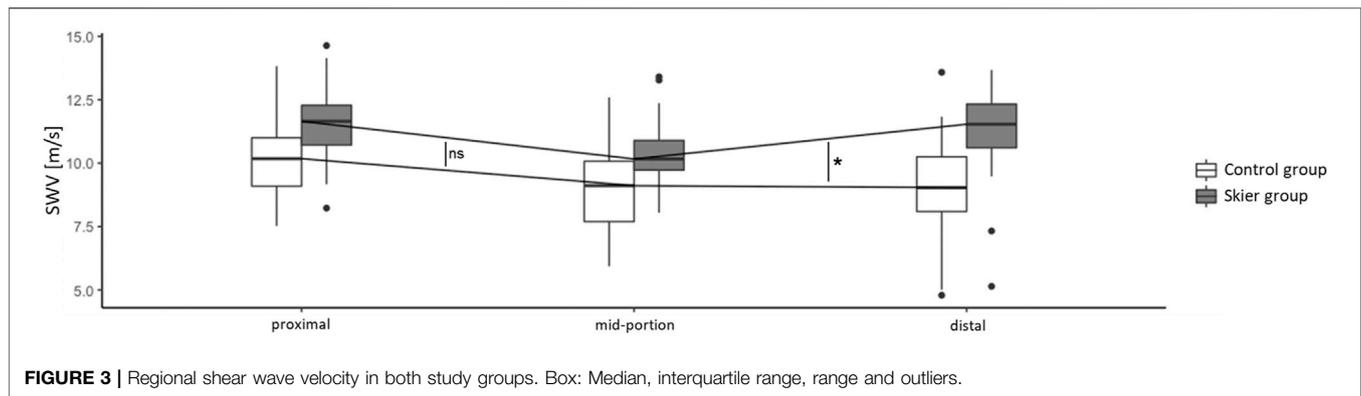


part of the off-season training period, in which also the present study was conducted, there is a particular focus on physical conditioning with 2–4 sessions of endurance training, 2–4 sessions of strength training, 1,2 sessions of explosive strength training and plyometrics, 2,3 sessions of agility and motor training, 3–5 sessions of stability and mobility training, and 1,2 sessions of cross training in other sports (Gilgien et al., 2018). The following inclusion criterion was applied: Physically active defined as more than one session of intense physical activity or more than 30 min of moderate physical activity per week. The number of participants recruited was limited by the number of active national competitive alpine skiers as part of the Swiss Alpine Ski Team. All skiers were monitored for health problems in a two-weekly interval with the Oslo Trauma Research Center (OSTRC) questionnaire for a minimum of 9 months prior to and up to the day of testing. Exclusion criteria were: 1) manifested signs of tendon disease or systemic pathology relevant to the purpose of the study; 2) acute PT tendon complaints; or 3) “severe” traumatic knee injuries leading to long-term training absences of more than 28 days

(Fuller et al., 2006) within the 9 months preceding the US assessments. The medical records were verified and updated during an additional check-up by a medical doctor prior to SWV assessments. Nine subjects from the skier group were excluded, as they met exclusion criteria; 4 were excluded due to exclusion criteria 2, and 5 were excluded due to exclusion criteria 3. SWE assessments in the skier group were performed at the start of the off-season training period in May. Controls were particularly recruited to be healthy and not having experienced patellar tendon-related knee pain within the last 12 months. All subjects were informed of the aim of the study and provided written consent. The study was approved by the local ethics committee (KEK-ZH-NR: 2017-01395).

## Ultrasound Assessment

US assessments and data processing were performed exactly as described in our validation study, which revealed *good* interoperator reliability (ICC of 0.736) and *very good* interday reliability (ICC of 0.904) (Götschi et al., 2021). One assessment was performed for each tendon by an experienced examiner; in total, 4 examiners were involved. The participant was in the supine position with adjustable support underneath the knee and a knee flexion angle of approximately 20°, and the right patellar tendon was examined (Martinoli, 2010). A US device (Aixplorer® Ultimate, Supersonic Imagine, Aix-en-Provence, France) capable of high frame-rate US acquisition equipped with a linear transducer (SL18-5) was used. The US transducer was held perpendicular to the skin, and parallel alignment with the fiber axis was ensured by observing and maximizing the fibrillar appearance of the intratendinous structure. Position and orientation of the US transducer was tracked throughout the scanning procedure with optical markers attached to it and an optical tracking system (FusionTrack 500, Atracsys LLC) (Figure 1A). 2D SWE and US brightness-mode (B-mode) data were projected into 3D space and aggregated using a weighted averaging scheme to yield a 3D voxel representation of the measurement (MATLAB 2020a; The MathWorks, Inc., Natick, MA, United States). The tendon was then segmented in the US B-mode volume, and the SWE volume was masked accordingly (3D slicer, version 4.10.2, (Kikinis et al., 2014)). To allow analysis of distinct PT regions, the masked SWE reconstruction was divided into three regions with two cuts positioned at a distance of 10 mm from the proximal and distal insertion (Figure 1B), analogous to the approach described in our validation study (Götschi et al., 2021). Briefly, the area of



interest was identified using landmarks placed during manual segmentation of the volume. Accordingly, the most distal point of attachment of the patella to the patellar tendon and the most proximal point of attachment of the tibia were marked for the proximal and distal sections of the PT. Further analysis was performed based on mean values for the respective regions.

## Statistical Analysis

To estimate the association of group membership while correcting for other potentially confounding variables with regional SWV, a multivariate approach is needed. Given the sample size available, including all factors of interest (including interaction effects) in one linear model may yield erroneous estimates due to overfitting. Hence, we opted for an alternative approach where we determined the linear model for inference by selecting the set of predictors with the best predictive performance in a leave-one-out validation scheme (maximum adjusted  $R^2$ ). Consequently, for factors not included in the final models, no effect estimates are available. Univariate comparisons between groups were conducted with independent samples t tests. Statistical analysis was performed with R (Team, 2021), and statistical significance was set at  $\alpha = 0.05$ .

## RESULTS

### Baseline Characteristics

The baseline characteristics of both study groups are summarized in Table 1.

### Overall Study Population

Linear regression modeling revealed group membership to be the only determining factor of SWV over the entire study population for all assessed tendon regions (overall, proximal, mid-portion, and distal), with skiers displaying higher SWV (Table 2).

### Predictive Factors of Shear Wave Velocity in Each Study Group

When assessing each study group separately, in the skier group, both subject age and sex were retained in the final regression model for the midportion region of the PT (Table 3). In the

control group, no predictors for mid-portion SWV were identified.

Figure 2 visualizes shear wave velocity differences between groups as well as the significant sex effect in the skier group and the absence thereof in the control group.

## Regional Shear Wave Velocity Patterns in Patellar Tendons

We found that the regional difference in SWV between the distal and mid-portion PTs differed between the skier and control groups ( $p = 0.023$ ). The two groups, however, did not differ with regard to the regional delta between the proximal and PT mid-portions ( $p = 0.599$ , Figure 3).

## DISCUSSION

This study found higher PT SWV in competitive alpine skiers than in healthy controls. No demographic factors were predictive of SWV in the entire study cohort. Male skiers had a higher SWV than female skiers, whereas no such difference was found in the control group. Furthermore, skiers displayed a larger SWV decrease from the distal tendon to its mid-portion.

### Higher Shear Wave Velocity in Competitive Alpine Skiers Than Healthy Controls

Physiological tendon hypertrophy and remodeling in response to altered loading regimes allows the tendon to cope with increased training volume and intensity. Moreover, optimization of muscle tendon unit performance requires both muscle and tendon to adapt, whereas the tendon is responsible for effective force transmission. In this context, lower tendon hysteresis has been reported in ski jumpers and runners compared to control subjects (Wiesinger et al., 2017). Pathological adaptations, on the other hand, lead to deterioration of the tendon structure, limiting the capacity for physical performance and increasing the risk of tendon rupture (Cook and Purdam, 2009; Ooi et al., 2016; Yasui et al., 2017). Competitive alpine skiers are exposed to tremendous loads both during off-season training and in the competition season (Supej and Holmberg, 2010; Hydren et al.,

2013; Gilgien et al., 2018). High accelerations combined with forward pushed, highly flexed knees induce large forces acting on the knee joint and, in particular, the PT (Alhammoud et al., 2020). Moreover, compared to other sports, particularly in competition situations the demands on the PT in alpine skiers are relatively high (90–120 s of high-intensity loading of the quadriceps muscles with peak ground reaction forces of up to four times body weight) (Supej and Holmberg, 2010). Therefore, off-snow training modalities are also designed to meet these unique demands, making extensive adaptations of the PT in skiers theoretically sound. Finally, such extraordinary demands can overwhelm the system's capacity for adaptation, which may manifest in a high prevalence of overuse complaints in this cohort (Fröhlich et al., 2020; Fröhlich et al., 2021). A closer understanding of the adaptive processes in response to long-term repetitive loading with regard to PT material properties is crucial in prevention and early detection strategies.

### Influence of Demographic Factors

When assessing intercohort differences, adjustment of confounding variables such as demographic factors is necessary. To do so, the selection of linear models with the best predictive performance is a suitable method (Stone, 1974). In our dataset, the effect of the tendon loading regime (i.e., group membership) outweighed biological factors such as weight, height, sex, age, tendon CSA, and tendon length. Zhang et al. reported lower stiffness in the PT of athletes; however, the inclusion criteria for the athletic cohort was a minimum of 4 h of exercise per week; hence, the inclusion criteria for the control and athlete groups are not comparable with our study (Zhang et al., 2015). Other studies agree with our finding: Increased PT SWV in athletes has been reported when compared to nonathletic cohorts (Zhang et al., 2015; Bayliss et al., 2016; Mersmann et al., 2017; Cristi-Sanchez et al., 2019; Dirrichs et al., 2019; Selcuk Can et al., 2021). A quantitative comparison of relative magnitude from our study shows a 1.17 times higher SWV in PT in skiers compared to the control group, whereas it is 1.47 when calculated with the results from Selcuk Can et al. (Selcuk Can et al., 2021). The difference may be explained by the different activity levels of the control and athlete groups in the two studies, but nevertheless, the two factors are in a similar range.

### Potential Influence of Different Loading Regimes

Furthermore, increased tendon SWV values have been reported to result from altered loading regimes (Malliaras et al., 2013; Bohm et al., 2015), confirming the tendon's ability to adapt to load and supporting our finding that the loading regime is the main factor inducing physiological tendon adaptation. Interestingly, a sex-specific difference in SWV was only found in the skier group, which may indicate that high loads must be present to elicit sex-specific adaptation mechanisms. Some studies suggest that there is a sex-specific difference in mechanical tendon properties (Kubo et al., 2003; Onambele et al., 2007; Tas et al., 2017), while others do not (Burgess et al., 2009; O'Brien et al., 2010; Morrison et al., 2015); hence, in the literature, there is no consensus in this regard. On the

one hand, hormone-based effects on tendon adaptation have been described: Acute exercise-induced increase of tendon collagen synthesis is inhibited by estrogen (Magnusson et al., 2007) and is therefore diminished in magnitude and time, compared with men (Miller et al., 2007). On the other hand, male subjects are both heavier and suspected to be able to generate higher knee extension moments than female subjects, leading to increased PT forces and subsequently inducing PT adaptation. In agreement with this hypothesis, Arampatzis et al. found a positive correlation between maximal knee extension moment and PT stiffness (Arampatzis et al., 2007). Another study found increased PT stiffness in heavily loaded legs, whereas no effect was found in light loaded legs (Kongsgaard et al., 2007). Furthermore, no significant correlation between knee extension torque and PT stiffness has been found in subjects with no specific training engagement (Mannarino et al., 2018), thus supporting our hypothesis. The literature states that female sex is a protective factor regarding patellar tendinopathies, referring to team sport athletes (Morton et al., 2017). Since the difference in PT SWV was observed in competitive alpine skiers but not in the control group, it may be assumed that lower forces applied in female recreational athletes and, therefore, overuse complaints at the PT occur less frequently.

### Differences in Regional Patellar Tendon Shear Wave Velocity

In the current study, different regional patterns in the PT SWV were found between skiers and controls, with significant differences between the delta from the mid-portion to the distal region. Functionally and clinically, proximal regions, mid-portions, and distal regions differ, and thus, it is expected that SWV as a quantification for tendon adaptation (i.e., collagen cross-linking) reflects the heterogeneous regional characteristics. Interestingly, Kongsgaard and others found an increase in proximal PT CSA after light and heavy training in healthy untrained men but a distal increase in CSA only after heavy training, with the training consisting of knee extension exercise (Kongsgaard et al., 2007). Since our study included only physically active subjects and yet the athletic cohort performs heavier physical activity, our finding is reflected by the results from Kongsgaard et al. (Kongsgaard et al., 2007). The precise structural adaptations that underlie elevated tendon SWV are currently unclear; nevertheless, the nonuniform adaptation behavior along the PT in response to the loading regime cannot be neglected. Thus, further research should implement a more sophisticated view regarding loading magnitude with regard to regional adaptations.

### Study Limitations

This study has limitations to be considered. Physical activity levels of control subjects were not quantified on a continuous scale, and thus, there are potentially highly active subjects included in the control group. Since high-level athletes usually have more muscle mass than recreational athletes, BMI between these groups significantly differs, hence representing a confounding factor. Furthermore, a challenge in assessing tendon SWV is the alignment between the transducer and tendon fiber orientation. Despite greatest caution in aligning

the transducer to the fiber orientation, situations where the fibers are not colinear over the entire measurement frame cannot be compensated for. Finally, tendon loading in the hours prior to or during the measurement was not controlled for; therefore, we asked the subjects to remain relaxed in the measurement position for 5 minutes and refrain from strenuous physical activity 24 h prior to the assessment. An interesting aspect that cannot be concluded from the present study and requires further investigation is whether there are differences in the SWV profiles of skiers in the different periods of a season.

## CONCLUSION

Competitive alpine skiers showed higher SWV values in PT than physically active control subjects. The tendon loading regime is likely a main cause for the observed adaptations. Within skiers, males showed higher SWV values than females in the control group; however, no sex-specific difference was found. Hence, the intracohort analysis indicates that vast loading magnitudes and volumes are required to elicit such effects. Differences in the regional SWV pattern in the two cohorts indicate PT tissue adaptations to be dependent on the anatomical location. Translating our findings toward clinical applications and prevention strategies, screening and appropriate strength exercise might represent a fundamental component; however, normative data for different cohorts are fundamental in turns of a meaningful screening program.

## DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because their access is restricted to protect the interests of the project partner Swiss-Ski and their athletes. Requests to access the datasets should be directed to joerg.spoerri@balgrist.ch.

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## ETHICS STATEMENT

The study was reviewed and approved by the local ethics committee (KEK-ZH-NR: 2017-01395). The patients/participants provided their written informed consent to participate in this study.

## AUTHOR CONTRIBUTIONS

JSp and TG conceptualized and designed the study. JSp, NS, and SH recruited the participants and organized the data collection. TG, NS, SH, VH and JSp collected the data. TG, JH, NS, SH, and VH processed the data, and JH and TG performed the statistical analysis. All authors substantially contributed to the interpretation of the data. TG and JH drafted the current manuscript; all authors revised it critically, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

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