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# Muscle-tendon unit length changes in knee extensors and flexors during alpine skiing

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## ABSTRACT

This study characterised the thigh muscle-tendon unit length variations (MTUv) in elite alpine skiing. MTUv were modelled for seven muscles from knee and hip angles in 17 national team skiers during 1602 cycles (546 Slalom (SL), 908 Giant-Slalom (GS), 136 Super-Giant (SG) and 12 Downhill (DH) cycles). The biarticular *rectus femoris* showed a dynamic pattern on both legs, especially in SL. On the other side, *vastii* displayed a stable length on the inside leg in all disciplines (37–46% of the cycle), contrasting with their dynamic behaviour on the outside leg being quasi-static for only 3% (SL) to 27% (DH) of the cycle. SL showed the largest amplitude of MTUv followed by GS, SG and DH. For *vastus lateralis*, MTUv was  $\sim 60\%Lr \cdot s^{-1}$  in SL but only  $\sim 12\%Lr \cdot s^{-1}$  in DH. In SL, a fine desynchronisation between both joints led to nearly constant MTUv (slow lengthening lasting  $\sim 45$ –51% of the cycle) for the biarticular hamstrings separated by faster variations during turn switch from outside to inside leg. In summary, biarticular MTUv were not characterised by single-joint behaviours, suggesting that extrapolating contraction regimen from knee joint only is not accurate in alpine skiing.

## ARTICLE HISTORY

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## KEYWORDS

Kinematic; elite skiers; knee angle; muscle length changes

## Introduction

Alpine skiers gain kinetic energy travelling down the slope and resist large compressive forces via predominant eccentric (Berg et al., 1995) and isometric (Alhammoud, Morel et al., 2020) muscle contractions. These contraction modes have been described based on knee angle kinematic (Berg & Eiken, 1999; Berg et al., 1995; Panizzolo et al., 2013). However, biarticular muscle-tendon units (MTU) are influenced by both knee and hip-joint movements with, for example, the *rectus femoris* (RF) being more affected by hip than knee angle (Hawkins & Hull, 1990). Although our understanding of muscle behaviour during on-snow alpine skiing directly impacts training as a large component of the skiers training is performed on-land, there are no studies on muscle kinematic in

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alpine skiing. Muscle kinematic during cyclic movement in the sagittal plane can be analysed using regression equations to model muscle lengths (Hawkins & Hull, 1990).

The aim of the study was thus to characterise the MTU length variations (MTU<sub>v</sub>) of the main thigh muscles in elite alpine skiers.

## Methods

### Participants

Seventeen national team alpine skiers [8 females ( $23 \pm 3$  yrs,  $168 \pm 5$  cm,  $64.0 \pm 4.9$  kg) and 9 males ( $25 \pm 5$  yrs,  $177 \pm 5$  cm,  $75.6 \pm 7.3$  kg)] volunteered for this study and signed an informed consent. The study was approved by the scientific and ethic committee of the Inter-University Laboratory of Human Movement Biology of the University of Lyon. All procedures conformed to the standards of the Declaration of Helsinki.

### General procedure

The right knee and hip-joint angles were continuously recorded using bi-axial electrogoniometers (SG150, Biometrics, Newport, UK) firmly secured directly on the skin as previously described (Alhammoud, Morel et al., 2020). Briefly, the sagittal plane of the goniometers was calibrated in three positions: seated, standing, crouched (Appendix 1). Data were recorded at 148 Hz by a data logger (TPM, Delsys) and normalised to the cycle as an inside leg (right turn, 0% to 50% of the cycle) plus outside leg (left turn, 50% to 100% of the cycle). The turn switch between legs was automatically identified using the functional minima of the resultant acceleration corresponding to the skier edge's change (Alhammoud, Morel et al., 2020). A total of 1602 cycles were analysed, including Slalom (SL,  $n = 546$ ), Giant Slalom (GS,  $n = 908$ ), Super Giant (SG,  $n = 136$ ) and Downhill (DH,  $n = 12$ ).

The study was conducted in Cerro Castor (Ushuaia, Argentina) during two consecutive seasons (September 2016 and August 2017). The athletes skied with their own ski prototypes matching the International Ski Federation (FIS) equipment rules in place since the start of the 2012/2013 season (International Ski Federation FIS, 2012). The standing height (distance from the bottom of the running surface of the ski to the ski boot sole) was limited to 50 mm. A new regulation occurred in 2017/2018 in GS only with a shortened minimum side-cut radius for men (30 m vs 35 m previously) and a minimum ski length of 193 cm (195 cm previously). Those specifications were used in August 2017. The runs were timed and the course settings matched FIS competition rules. The number of gates ranged from 11 (DH) to 46 (SL); the vertical drop ranged from 89 m (SL) to 514 m (SG). The temperatures measured during the 2017 runs increased from 1.1°C to 3.5°C during the training sessions (Alhammoud, Oksa et al., 2020). Visibility was good for 67.7% of the training and reduced to 32.3%. Most trainings took place on natural snow (4.6% on artificial snow).

### Calculations

Angles were low-pass filtered (fourth-order Butterworth, cut-off frequencies of 0.5, 1, 2, and 2.5 Hz for DH, SG, GS and SL, respectively) and derived to compute the angular velocity (Alhammoud, Morel et al., 2020). The MTU length of the RF, *vastus medialis* (VM), *vastus*

**Table 1.** Parameters used for the calculation of the relative muscle-tendon unit (MTU) lengths.

Muscle	C1	C2	C3	C4	Lr
VM	0.489	0	$3.07e^{-3}$	$-1.53e^{-5}$	0.596
RF	1.107	$-1.5e^{-3}$	$1.99e^{-3}$	0	1.193
VL	0.569	0	$4.06e^{-3}$	$-2.07e^{-5}$	0.716
BFlh	1.048	$2.09e^{-3}$	$-1.6e^{-3}$	0	1.067
BFsh	0.600	0	$1.03e^{-4}$	$-1.21e^{-5}$	0.509
SM	1.027	$1.99e^{-3}$	$-2.22e^{-3}$	0	0.977
ST	0.987	$2.07e^{-3}$	$-1.78e^{-3}$	0	0.983

The relative MTU length (in % of resting length, Lr) was calculated as  $(C1 + C2xHR + C3xKR + C4xKR^2)/Lr$ , with HR and KR representing the hip and knee angle in degree ( $0^\circ$  = full extension) and Lr the resting MTU length. Formulae (Hawkins & Hull, 1990) and Lr of the hamstrings (Le Sant et al., 2015) and quadriceps (Xu et al., 2018) were obtained from the literature.

*lateralis* (VL), *biceps femoris* long head (BFlh), *biceps femoris* short head (BFsh), *semitendinosus* (ST) and *semimembranosus* (SM) were modelled in Matlab® based on the equations adapted from Hawkins & Hull (1990). Briefly, linear regression equations using knee and hip angles were used for all muscles except for the single-joint muscles crossing the knee (i.e., BFsh, VM, VL) for which quadratic regression equations were used. The length was normalised to the resting length (Lr) computed with Hawkins & Hull (1990) formulae using the knee and hip slack angles from the literature (Le Sant et al., 2015; Xu et al., 2018) (Table 1). These formulae are valid for hip and knee angles of 60–180° (Hawkins & Hull, 1990), corresponding to the range reported for elite alpine skiers (Alhammoud, Morel et al., 2020). MTU behaviour was defined as quasi-static within a range of  $\pm 2.9\%Lr.s^{-1}$  as this was similar to the threshold of  $20\%.s^{-1}$  previously defined from knee monoarticular muscles (Alhammoud, Morel et al., 2020). The negative and positive MTU velocities beyond this threshold were defined as the shortening and lengthening phases, respectively.

## Results

Figures 1 and 2 illustrate the instantaneous MTUv (mean $\pm$ 95%CI) according to four disciplines and seven muscles. It can be visually observed that instantaneous differences between the muscles and the disciplines were present at various cycle timeframes.

### Knee extensors

The MTUv of the VM remained quasi-static for 49% (SL), 62% (GS), 72% (SG) and 73% (DH) of the cycle; was lengthening for 25% (SL), 22% (GS), 16% (SG) and 14% (DH) of the cycle; and was shortening the remaining time (Figures 1 and 2, Appendix 2). The MTUv of the VL remained quasi-static for 50% (SL), 66% (GS), 71% (SG) and 72% (DH), and was lengthening for 24% (SL), 19% (GS), 16% (SG) and 15% (DH) of the cycle. The MTUv of the RF remained quasi-static for 20% (SL), 42% (GS), 52% (SG) and 68% (DH), and was lengthening for 24% (SL), 31% (GS), 26% (SG) and 21% (DH) of the cycle.

### **Knee flexors**

The MTUv of the BFlh remained quasi-static for 16% (SL), 72% (GS), 70% (SG) and 89% (DH), and was lengthening for 57% (SL), 17% (GS), 17% (SG) and 1% (DH) of the cycle. The MTUv of the BFsh remained quasi-static for 11% (SL), 25% (GS), 28% (SG) and 24% (DH), and was lengthening for 51% (SL), 34% (GS), 33% (SG) and 44% (DH) of the cycle. The MTUv of the SM remained quasi-static for 15% (SL), 42% (GS), 47% (SG) and 61% (DH), and was lengthening for 61% (SL), 28% (GS), 25% (SG) and 15% (DH) of the cycle. The MTUv of the ST remained quasi-static for 15% (SL), 62% (GS), 57% (SG) and 74% (DH), and was lengthening for 60% (SL), 24% (GS), 21% (SG) and 8% (DH) of the cycle.

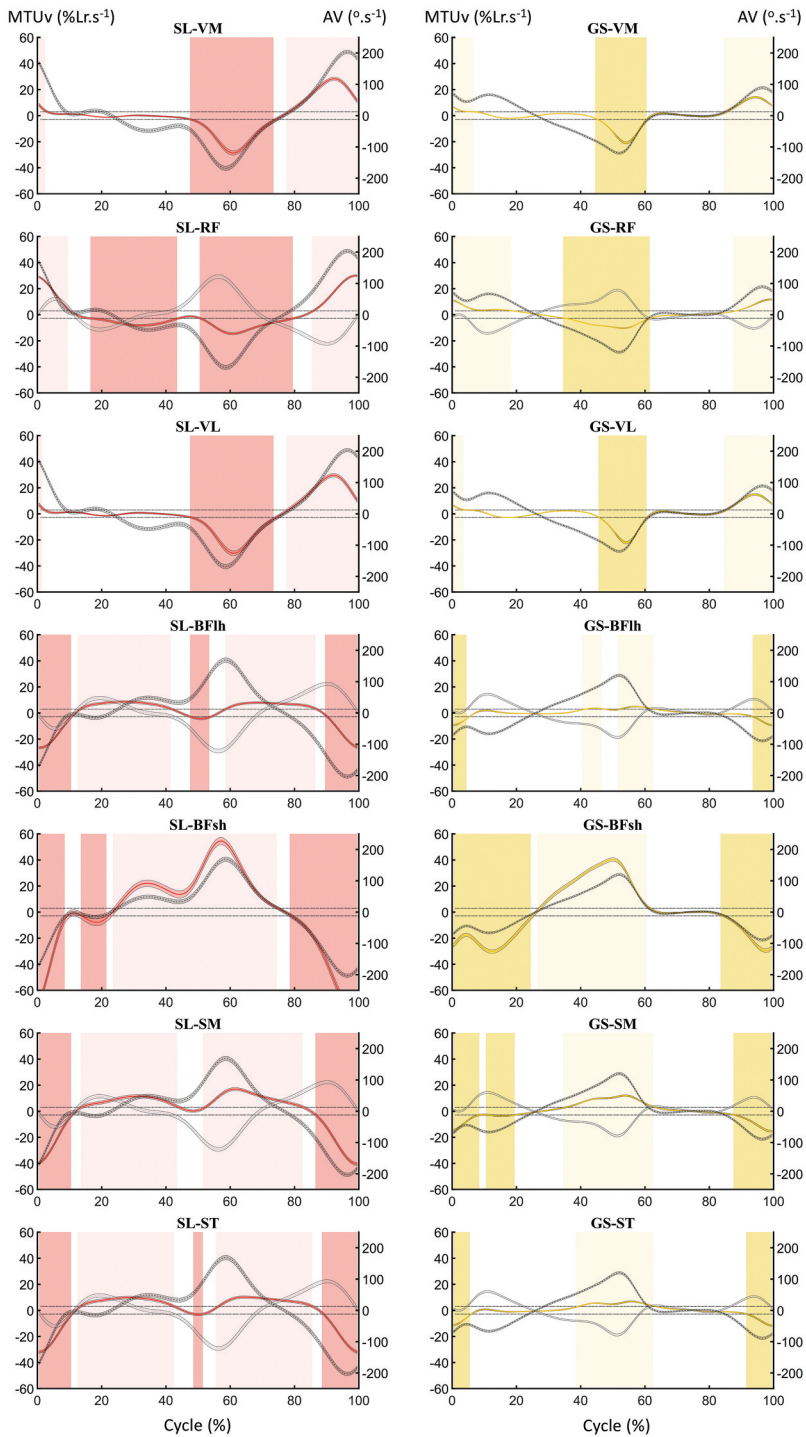
### **Discussion and implications**

The aim of the study was to propose a simplified model of thigh MTUv in alpine skiing. The current study showed that both *vastii* displayed a relatively stable length on the inside leg in all disciplines (37–46% of the cycle, [Figures 1 and 2](#)), contrasting with their highly dynamic behaviour on the outside leg being quasi-static for only 3% (SL) to 27% (DH) of the time. MTUv differed between muscles within a given discipline (e.g.,  $35\%Lr.s^{-1}$  for BFlh vs  $129\%Lr.s^{-1}$  for BFsh in SL). Current data also showed that the desynchronisation between both joints led to nearly constant MTUv for the biarticular hamstrings in SL, mainly with slow lengthening ( $\sim 45\text{--}51\%$  of the cycle, [Figure 1](#)) separated by shorter and faster shortening phases during edge's change from outside to inside leg.

### **Knee extensors**

While alpine skiing has been considered to require a continuous tension of the quadriceps MTU to maintain knee angle ([Schneebeli et al., 2020](#); [Seynnes et al., 2011](#)), our results showed a wide range of variation of the MTU length across disciplines and muscles. [Berg et al. \(1995\)](#) reported a biphasic RF activation in GS acting as knee extensor on the outside leg and hip flexor on the inside leg. They described an eccentric-concentric quadriceps sequence on the outside leg in GS with traditional skis whereas [Frick & Schmidtbleicher \(1997\)](#) reported a concentric-eccentric sequence in SL. Our results add information regarding the timing and amplitude of the MTU length and velocity changes in four alpine disciplines. For the VL, MTUv was  $\sim 60\%Lr.s^{-1}$  in SL but only  $\sim 12\%Lr.s^{-1}$  in DH. RF was lengthened on the initial phase of the inside leg in SL, then it shortened ( $\sim 15\%Lr.s^{-1}$ ) during the cycle and was rapidly lengthened ( $\sim 29\%Lr.s^{-1}$ ) after  $\sim 86\%$  of the cycle. RF initiated its shortening phase earlier ( $\sim$ at 20% of the cycle) in SL, due to the hip movement, whereas the *vastii* had a shortening phase after 49% of the cycle only (e.g., on the outside leg). The total quasi-static phase was reduced in RF (17–45% of the cycle) as compared to the monoarticular *vastii* (32–53% of the cycle) in all disciplines but DH.

[Frick & Schmidtbleicher \(1997\)](#) described a bending phase for hip and knee on the inside leg before the pole touch, followed by an extension phase for both joints. In alpine skiing, knee and hip motions are considered synchronised, ([Berg et al., 1995](#)) with both joints being extended on the outside leg and flexed during the transition and inside leg. This synchronisation should maintain the RF MTU length but our data showed that it



**Figure 1.** Muscle-tendon unit length variation (MTUv) in technical disciplines of elite skiing (Slalom, SL, red; Giant Slalom, GS, yellow). The quasi-static actions with a displacement below 2.9% of the MTU relative length (Lr) per second are indicated with a white background. MTU shortening (negative values) and lengthening (positive values) are indicated by a dark and light background. The leg is inside from 0 to 50%,



and outside from 50 to 100%. VM: *vastus medialis*, VL: *vastus lateralis*, RF: *rectus femoris*, BFsh: *biceps femoris* short head, BFlh: *biceps femoris* long head, SM: *semimembranosus*, ST: *semitendinosus*. The dark and light grey curves represent the absolute knee and hip-joint angular velocities ( $AV, ^\circ.s^{-1}$ ) respectively, and the sign is relative to the MTU length direction of change for the positive/negative joint velocity to correspond to the lengthening/shortening of the MTU, (i.e. the sign of the knee AV has been arbitrarily inverted for the VM, VL and RF; and the sign of the hip AV has been inverted for the BFlh, SM and ST). Curves are displayed as mean  $\pm 95\%$ CI. See Appendix 2 for cluster limits.

exhibited the lowest quasi-static phase among the quadriceps muscles in SL (17% of the cycle for RF vs. 35% for VM and 32% for VL). Elite skiers stabilise the centre of mass position by postural adjustments of ankle and trunk (LeMaster, 2010), thereby eliciting slight rotations of the hip joint when the knee is locked. Therefore, bi-articular MTUv reflects postural adjustments and stabilisation of the skier (Figure 1) (LeMaster, 2010). This finding is in contradiction with previous estimations in free ski-carving predicting a nearly constant length of the RF throughout the ski cycle in recreational skiers (Kröll et al., 2010) who have a more static profile than elite athletes.

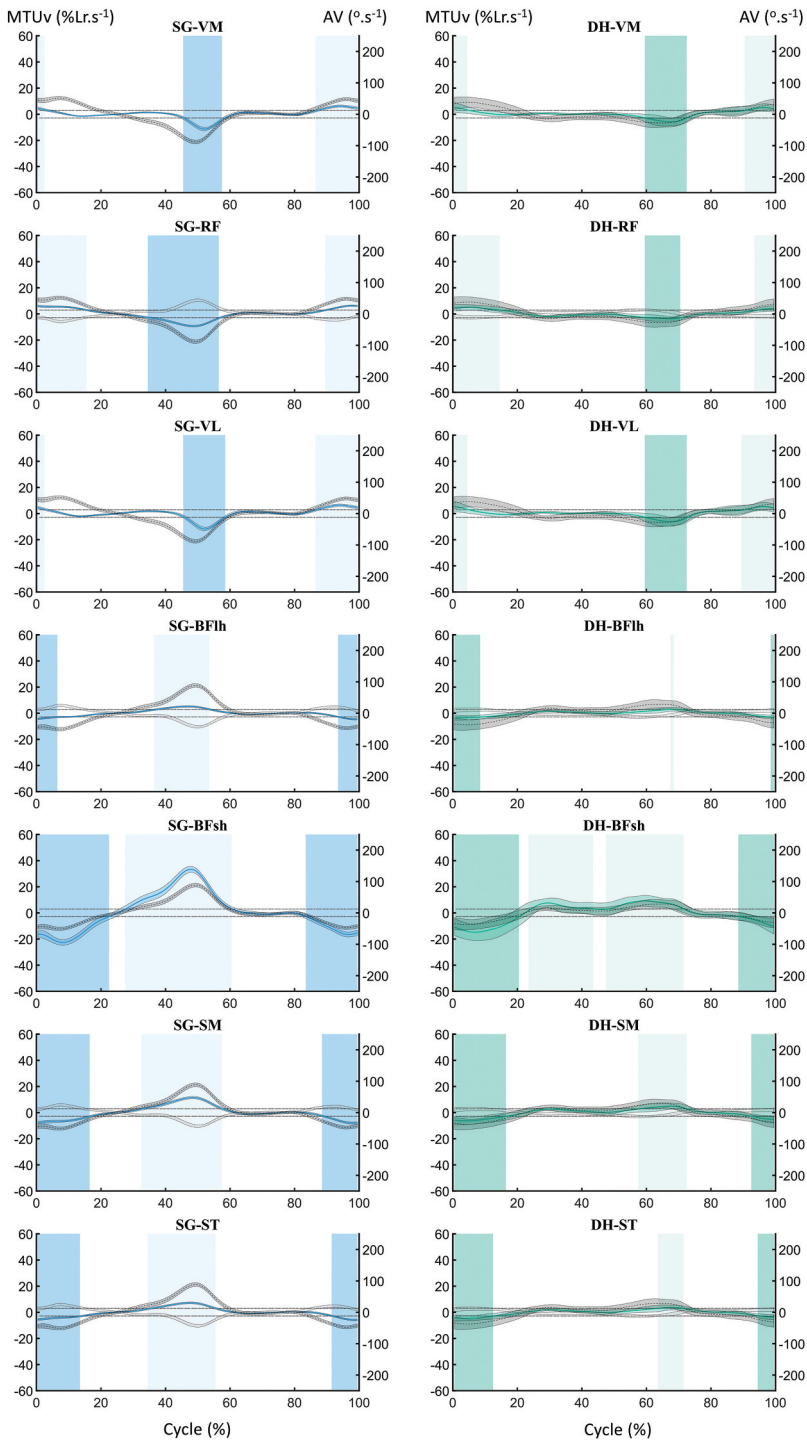
### **Hip extensors**

Biarticular hamstrings displayed a reversed pattern to the RF with a double plateau in SL (i.e., 2 slow lengthening plateaus separated by a quasi-static phase at the switch from inside to outside leg). Frick & Schmidbleicher (1997) suggested that hip extensors worked isometrically during the first part of the outside leg in SL and eccentrically during the second part, after pole touch. The current data showed that hip extensors displayed a lengthening-shortening sequence separated by a quasi-static phase of variable duration depending on the discipline (Figures 1 and 2). For example, the BFlh displayed an increasing duration of the quasi-static coupling phase on the outside leg from  $\sim 2\%$  of the cycle in SL to  $\sim 39\%$  in SG. Thus, a stretch-shortening cycle may occur in the technical disciplines displaying the shortest quasi-static transition. The current difference with Frick & Schmidbleicher (1997) may be attributed to the changes in skis shape in the past 20 years and to the different methodology used (MTU length modelling vs. 3D video joint kinematic analysis).

### **Methodological considerations**

The equations used here were developed from *in vitro* isolated muscles (Hawkins & Hull, 1990). These equations were recently validated for monoarticular muscles, but their accuracy for biarticular muscles may be limited (Retailleau, 2019). Indeed, BFlh MTUv is affected by hip abduction with feet spacing (Retailleau, 2019), potentially affecting the estimations during ski turns. Adduction/abduction and internal/external rotation movements also affect 2D models (Retailleau, 2019), but skiers maintain their feet parallel while skiing. Moreover, although 2D and 3D articular kinematic are not correlated in the frontal plane, they are correlated in the sagittal plane (Schurr et al., 2017), and 2D models are equivalent to 3D models for the *vastii* irrespective of foot position (Retailleau, 2019). Thus, although a 3D model is considered the 'gold standard', a 2D analysis is a practical solution during ski training. Of note, the current study was conducted in elite athletes





**Figure 2.** Muscle-tendon unit length variation (MTUv) in speed disciplines of elite skiing (Super Giant, SG, blue; Downhill, DH, green). The quasi-static actions with a displacement below 2.9% of the MTU relative length ( $L_r$ ) per second are indicated with a white background. MTU shortening (negative values) and lengthening (positive values) are indicated by a dark and light background. The leg is inside from 0 to

50%, and outside from 50 to 100%. VM: *vastus medialis*, VL: *vastus lateralis*, RF: *rectus femoris*, BFsh: *biceps femoris* short head, BFlh: *biceps femoris* long head, SM: *semimembranosus*, ST: *semitendinosus*. The dark and light grey curves represent the absolute knee and hip-joint angular velocities (AV,  $^{\circ}.s^{-1}$ ) respectively, and the sign is relative to the MTU length direction of change for the positive/negative joint velocity to correspond to the lengthening/shortening of the MTU, (i.e. the sign of the knee AV has been arbitrarily inverted for the VM, VL and RF; and the sign of the hip AV has been inverted for the BFlh, SM and ST). Curves are displayed as mean $\pm$ 95%CI. See Appendix 2 for cluster limits.

during racing training, with a preparation time limited to 10 min to avoid disturbing the athletes.

Lastly, the filtering with low cut-off frequencies may have blunted vibration frequencies involved in alpine skiing (Fasel et al., 2016) and neglected the shock absorber role of the MTU. The proportion of quasi-static activity may also change with a different cut-off definition.

### **Practical applications**

Due to the specific muscle and neural (Fang et al., 2004) adaptations to the type of muscle contraction used during training, fitness coaches should be aware of the impact of concomitant hip and knee positions on MTU lengths to implement various joint angle combinations matching those of the ski cycle. This is particularly relevant for elite alpine skiers as on-snow training is seasonal and athletes largely rely on dry-land strength and conditioning. In line with the Lombard's paradox already described during squatting and cycling (Andrews, 1987), the biarticular hamstrings are likely acting as antagonists and agonists during the double knee and hip extension at the beginning of the outside leg phase. However, EMG would also be needed to characterise the contraction regimen. This work could serve as a basis for the development of ski-racing exercises specific to the muscle kinematic of the inside and outside leg along with the sequential organisation of the movement.

### **Conclusion**

The current study showed a specific dynamic pattern in SL with the largest amplitude of MTUv followed by GS, SG and DH. For VL, MTUv was  $\sim 60\%Lr.s^{-1}$  in SL but only  $\sim 12\%Lr.s^{-1}$  in DH. Moreover, biarticular MTUv were not characterised by knee- or hip-joint single behaviour, suggesting that extrapolating muscle kinematic from knee joint only is not accurate. In SL, a fine desynchronisation between both joints led to nearly constant MTUv (slow lengthening lasting  $\sim 45$ - $51\%$  of the cycle) for the biarticular hamstrings separated by faster variations during turn switch from outside to inside leg. The biarticular RF muscle showed a dynamic pattern of MTUv on both legs especially in SL whereas *vastii* displayed a dynamic outside leg pattern along with a quasi-static pattern on the inside leg for all disciplines.

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## Disclosure statement

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## Data availability statement

Data are available from the corresponding author upon reasonable request.

## References

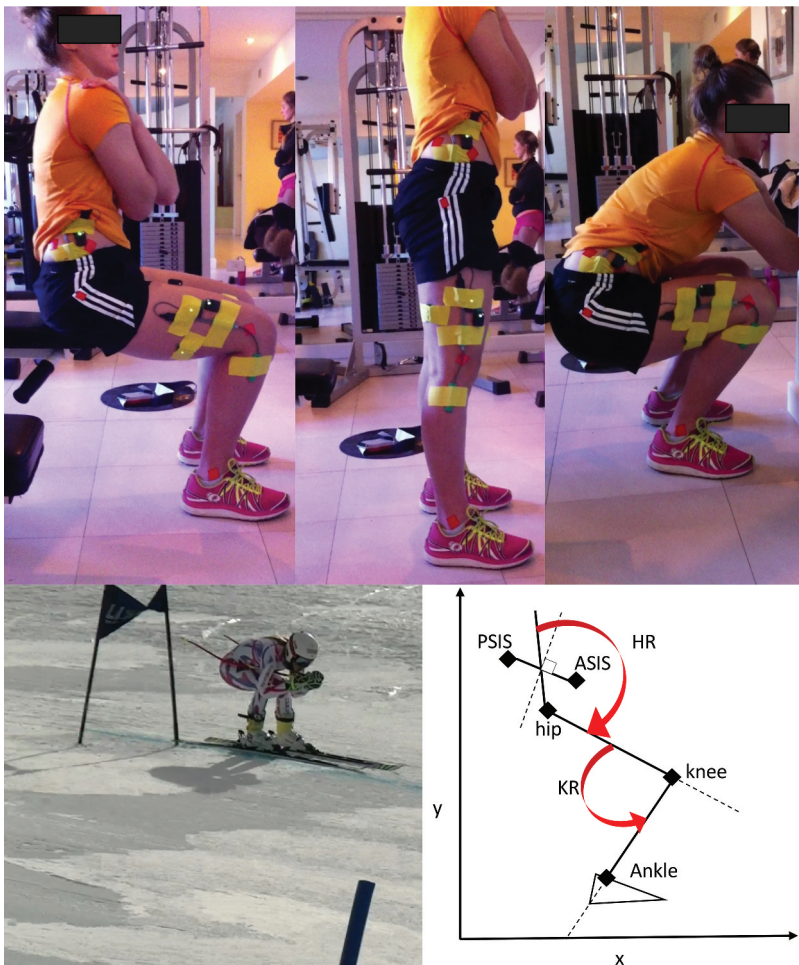
- Alhammoud, M., Morel, B., Hansen, C., Meyer, F., & Hautier, C. A. (2020). On-field ski kinematic according to leg and discipline in elite alpine skiers. *Frontiers in Sports and Active Living*, 2, 56. <https://doi.org/10.3389/fspor.2020.00056>
- Alhammoud, M., Oksa, J., Morel, B., Hansen, C., Chastan, D., & Racinais, S. (2020). Thermoregulation and shivering responses in elite alpine skiers. *European Journal of Sport Science*, 1–12. <https://doi.org/10.1080/17461391.2020.1754470>
- Andrews, J. G. (1987). The functional roles of the hamstrings and quadriceps during cycling: Lombard's Paradox revisited. *Journal of Biomechanics*, 20(6), 565–575. [https://doi.org/10.1016/0021-9290\(87\)90278-8](https://doi.org/10.1016/0021-9290(87)90278-8)
- Berg, H. E., Eiken, O., & Tesch, P. A. (1995). Involvement of eccentric muscle actions in giant slalom racing. *Medicine & Science in Sports & Exercise*, 27(12), 1666–1670. <https://doi.org/10.1249/00005768-199512000-00013>
- Berg, H. E., & Eiken, O. (1999). Muscle control in elite alpine skiing. *Medicine and Science in Sports and Exercise*, 31(7), 1065–1067. <https://doi.org/10.1097/00005768-199907000-00022>
- Fang, Y., Siemionow, V., Sahgal, V., Xiong, F., & Yue, G. H. (2004). Distinct brain activation patterns for human maximal voluntary eccentric and concentric muscle actions. *Brain Research*, 1023(2), 200–212. <https://doi.org/10.1016/j.brainres.2004.07.035>
- Fasel, B., Lehot, C., Spörri, J., Müller, E., & Aminian, K. (2016). *Body vibration and its transmission in alpine ski racing. XIV International Symposium on 3D Analysis of Human Movement*, Taipei, Taiwan (pp. 332–335).
- Frick, U., & Schmidbleicher, D. (1997). Types of muscle action of leg and hip extensor muscles in slalom. In E. Müller, H. Schwameder, E. Kornexl, & C. Raschner (Eds.), *Science and skiing* (pp. 262–271). Taylor and Francis (UK).
- Hawkins, D., & Hull, M. L. (1990). A method for determining lower extremity muscle-tendon lengths during flexion/extension movements. *Journal of Biomechanics*, 23(5), 487–494. [https://doi.org/10.1016/0021-9290\(90\)90304-L](https://doi.org/10.1016/0021-9290(90)90304-L)

- International Ski Federation FIS. (2012). *Specifications for alpine competition equipment*. Self-Publisher. Edition 2012/13 ed.
- Kröll, J., Wakeling, J. M., Seifert, J. G., & Müller, E. (2010). Quadriceps muscle function during recreational alpine skiing. *Medicine & Science in Sports & Exercise*, 42(8), 1545–1556. <https://doi.org/10.1249/MSS.0b013e3181d299cf>
- Le Sant, G., Ates, F., Brasseur, J. L., & Nordez, A. (2015). Elastography study of hamstring behaviors during passive stretching. *PLoS One*, 10(9). <https://doi.org/10.1371/journal.pone.0139272>
- LeMaster, R. (2010). Ultimate Skiing. *Human Kinetics*, 226.
- Panizzolo, F. A., Marcolin, G., & Petrone, N. (2013). Comparative evaluation of two skiing simulators as functional training devices for recreational skiers. *Journal of Sports Science & Medicine*, 12(1), 151–158. eCollection 2013.
- Schneebeli, A., Visconti, L., Cescon, C., Clijsen, R., Giardini, G., Arizzio, M. E., & Barbero, M. (2020). Tendon morphological changes after a prolonged ski race can be detected by ultrasound echo intensity. *Journal of Foot and Ankle Research*, 13(1), 34. <https://doi.org/10.1186/s13047-020-00398-9>
- Schurr, S. A., Marshall, A. N., Resch, J. E., & Saliba, S. A. (2017). Two-dimensional video analysis is comparable to 3D motion capture in lower extremity movement assessment. *International Journal of Sports Physical Therapy*, 12(2), 163–172.
- Seynnes, O. R., Koesters, A., Gimpl, M., Reifberger, A., Niederseer, D., Niebauer, J., Pirich, C., Müller, E., & Narici, M. V. (2011). Effect of alpine skiing training on tendon mechanical properties in older men and women. *Scandinavian Journal of Medicine & Science in Sports*, 21 (Suppl 1), 39–46. <https://doi.org/10.1111/j.1600-0838.2011.01340.x>
- Xu, J., Hug, F., & Fu, S. N. (2018). Stiffness of individual quadriceps muscle assessed using ultrasound shear wave elastography during passive stretching. *Journal of Sport and Health Science*, 7(2), 245–249. <https://doi.org/10.1016/j.jshs.2016.07.001>

## Appendices

### Appendix 1: Goniometer's calibration procedure

*Upper panel:* The goniometers were individually calibrated on the participants the day before the ski run using a video analysis (kinovea©, [www.kinovea.org](http://www.kinovea.org)) based on three positions (standing, seated, crouched) and their location was marked with an indelible marker. Retro-reflective markers were placed on the lateral malleolus, lateral femoral condyle, greater trochanter, anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS). Biaxial goniometers were placed with double-sided adhesive tape by the same tester on the right knee and hip and secured with tape. *Bottom left panel:* The goniometers were placed at the same location under the racing suit while the skiers performed their regular competition training. *Bottom right panel:* Joint angles definition. The shank was defined as the vector from the lateral femoral epicondyle to the lateral malleolus and the thigh as the vector from the lateral epicondyle to the greater trochanter. The pelvis was defined as the vector from the mid-ASIS to the mid-PSIS.



**Appendix 2: Cluster limits (% cycle) for the MTU length changes per discipline and per muscle.**

	Phase	SL	GS	SG	DH
<b>VM</b>	<b>Shortening</b>	[49–74]	[46–61]	[47–58]	[61–73]
	<b>Quasi-static</b>	[4–48;75–78]	[8–45;62–85]	[4–46;59–87]	[6–60;74–91]
	<b>Lengthening</b>	[1–3;79–100]	[1–7;86–100]	[1–3;88–100]	[1–5;92–100]
<b>RF</b>	<b>Shortening</b>	[18–44;52–80]	[36–62]	[36–57]	[61–71]
	<b>Quasi-static</b>	[11–17;45–51;81–86]	[20–35;63–88]	[17–35;58–90]	[16–60;72–94]
	<b>Lengthening</b>	[1–10;87–100]	[1–19;89–100]	[1–16;91–100]	[1–15;95–100]
<b>VL</b>	<b>Shortening</b>	[49–74]	[47–61]	[47–59]	[61–73]
	<b>Quasi-static</b>	[3–48;75–78]	[5–46;62–85]	[4–46;60–87]	[6–60;74–90]
	<b>Lengthening</b>	[1–2;79–100]	[1–4;86–100]	[1–3;88–100]	[1–5;91–100]
<b>BFsh</b>	<b>Shortening</b>	[1–11;49–54;91–100]	[1–5;95–100]	[1–7;95–100]	[1–9;100]
	<b>Quasi-static</b>	[12–13;43–48;55–59;88–90]	[6–41;48–52;64–94]	[8–37;55–94]	[10–68;70–99]
	<b>Lengthening</b>	[14–42;60–87]	[42–47;53–63]	[38–54]	[69]
<b>BFsh</b>	<b>Shortening</b>	[1–9;15–22;80–100]	[1–25;85–100]	[1–23;85–100]	[1–21;90–100]
	<b>Quasi-static</b>	[10–14;23–24;76–79]	[26–27;62–84]	[24–28;62–84]	[22–24;45–48;73–89]
	<b>Lengthening</b>	[25–75]	[28–61]	[29–61]	[25–44;49–72]
<b>SM</b>	<b>Shortening</b>	[1–11;88–100]	[1–9;12–20;89–100]	[1–17;90–100]	[1–17;94–100]
	<b>Quasi-static</b>	[12–14;45–52;84–87]	[10–11;21–35;64–88]	[18–33;59–89]	[18–58;74–93]
	<b>Lengthening</b>	[15–44;53–83]	[36–63]	[34–58]	[59–73]
<b>ST</b>	<b>Shortening</b>	[1–11;50–52;90–100]	[1–6;93–100]	[1–14;93–100]	[1–13;96–100]
	<b>Quasi-static</b>	[12–13;44–49;53–56;87–89]	[7–39;64–92]	[15–35;57–92]	[14–64;73–95]
	<b>Lengthening</b>	[14–43;57–86]	[40–63]	[36–56]	[65–72]

VM: *vastus medialis*, VL: *vastus lateralis*, RF: *rectus femoris*, BFsh: *biceps femoris short head*, BFlh: *biceps femoris long head*, SM: *semimembranosus*, ST: *semitendinosus*. SL: Slalom, GS: Giant Slalom, SG: Super Giant Slalom, DH: Downhill.