FATIGUE ALTERS THE BIOMECHANICS OF TURNS WHILE RUNNING

Matteo Zago[1,2], Chiarella Sforza[3], Virgilio Ferruccio Ferrario[3], Fabio Esposito[3] and Manuela Galli[1,2]

Dept. of Electronics Information and Bioengineering, Politecnico di Milano, Italy[1]
E4Sport Lab, Politecnico di Milano, Italy[2]
Dept. of Biomedical Sciences for Health, Università degli Studi di Milano, Italy[3]

This study identified the effects of fatigue on lower limb kinematics while running with repeated 180°-turns. An increased stiffness of the pivoting limb was observed in terms of a reduction of hip and knee flexion angles, and an increase of hip abduction and internal rotation. We concluded that muscle fatigue can trigger a sequence of adaptations that were previously found to expose the athlete to an increasing risk of ligament injury. These results expand the base of evidence for the development of field-based prevention programs.

KEYWORDS: ACL, change of direction, injury prevention, cutting maneuvers, kinematics.

INTRODUCTION: In team sports, the most frequent injuries causing more than four-weeks absence from competition are anterior cruciate ligament (ACL) lesions and medial collateral ligament (MCL) sprains. Turns (180°-directional changes) and cutting maneuvers are critical for a ligament's integrity since the fast decelerations produce anterior shear of the tibia relative to the femur, which is counteracted by the ACL and MCL, and eccentric contraction of the knee extensors and co-activation of the knee flexors (Besier et al. 2001, Brown et al., 2014).
The alteration of neuromuscular control during cutting can increase the likelihood of ligamentous injuries (Hewett et al. 2016; Read et al. 2016). A combination of reduced hip flexion angle, increased hip adduction and internal rotation, knee valgus and external rotation, shallow knee flexion angles and high dorsiflexion of the ankle may place the ACL to risk of failure (Alentorn-Geli et al. 2009; Hewett et al. 2016; Rafeeuddin et al. 2016). Peripheral (muscular) fatigue affects neuromuscular control, causing an increased joint laxity that may elevate injury risk. However, there is still no consistency among investigators regarding the effects of neuromuscular fatigue on knee, hip and ankle joint angles during exercise (Barber-Westin & Noyes 2017, Chappel et al., 2005). Therefore, this study aimed to evaluate the effect of fatigue on joint kinematics throughout a high-intensity protocol involving repeated turns. We hypothesized that muscular fatigue can induce unsafe patterns for the knee ligaments. The knowledge gained from studying these mechanisms would help in designing prevention programs.

METHODS: Twenty male physically-active sports science students (age: 18-23 years, BMI: 20.8-24.4 $kg \cdot m^{-2}$) participated in the study. They were right-footed (Elias et al., 1998), with no history of knee injuries, and possessed a medical certificate valid for competitive sport. This observational case-series study involved two sessions on separate days: (i) maximum oxygen uptake ($\dot{V}O_{2,max}$) and maximal aerobic speed (MAS) test (Ciprandi et al. 2017); (ii) 5-m shuttle running trial lasting 5 minutes at an average shuttle speed (v_{sh}) of 75% of subjects' MAS.
$\dot{V}O_2$ was measured with a portable metabolimeter (K4b^2, Cosmed, Italy). In the recovery period, peak blood lactate concentration ($[La]_b$) was measured (LacPro, BST, Germany). After the shuttle trial, subjects provided a rating of perceived exertion (RPE, 6-20 Borg scale). During the shuttle session, the instantaneous position of 17 reflective markers (sacrum; right and left acromia, olecranons, radius styloid processes, SIASs, femoral lateral epicondyles, lateral malleoli, calcanei, feet) were recorded at 60 Hz by an optoelectronic motion capture system (SMART-E, BTS, Italy), simultaneously with the metabolic measurements.
The stance phase (initial contact to toe-off) of the pivoting limb during right and left turns was determined. Hip joint angles were computed as the relative rotation of the pelvis and hip local reference systems (Euler ZYX). Knees and ankles were modelled as one degree-of-freedom

joints. Peak joints flexion and range-of-motion (RoM) were computed during the stance phase, as well as minimum center of mass (CoM) vertical position, normalized to participants' stature. The Euclidean norm of the 3D CoM velocity vector was obtained at initial contact and toe-off. Preliminary information on muscle activation was obtained from a subset of n=8 subjects; surface EMG electrodes were placed on the right Biceps Femoris (BF) and Gastrocnemius Lateralis (GL). Raw EMG data were band-pass filtered, full-wave rectified and normalized by the maximum EMG value for each muscle. Root mean square (RMS) value, median frequency and activation time (RMS>50% peak) were computed.
During the 5-min shuttle run, kinematic data were considered for both limbs and for five turns in the first minute (fresh condition), and for the last five turns (fatigued condition, Figure 1).
Mean values were then submitted to a two-way analysis of variance (ANOVA) with factors side (right, left) and condition (fresh, fatigued), with repeated measures on both factors. The magnitude of related effects was computed as partial eta squared (η^2). Fatigue-induced effects in EMG variables were compared with Wilcoxon signed rank tests; non-parametric effect sizes (ES) were computed. Significance level was set at p=0.05.

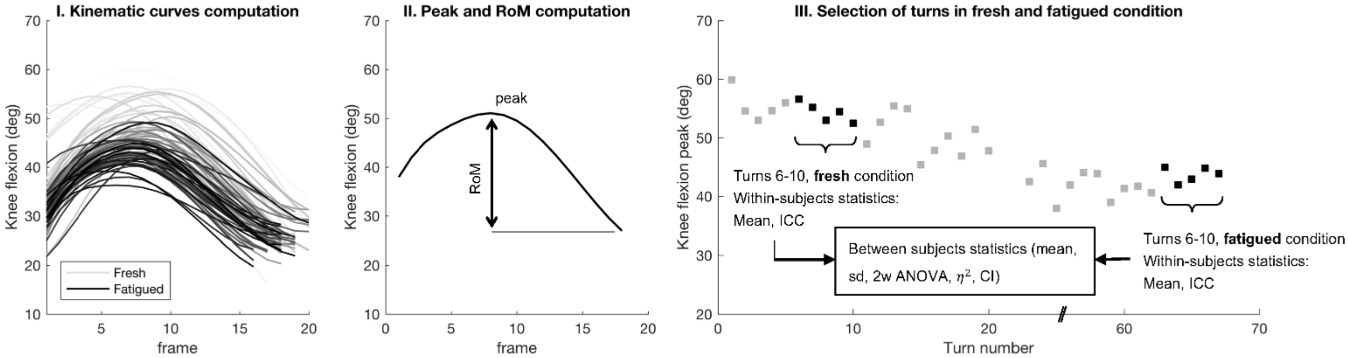

Figure 1: data extraction and statistical analysis process for kinematic variables.

RESULTS: Participants were homogeneous in terms of shuttle speed, as MAS ranged between 3.67 and 4.69 $m \cdot s^{-1}$. RPE ranged from "hard" to "maximum exertion" (RPE 16-20), %HR and $\%\dot{V}O_{2,max}$ were around 90% and post-exercise $[La]_b$ ranged from 5.4 to 15.5 mM.
Table 1 show that both hip and knee flexion peak and RoM significantly decreased with fatigue (condition factor, p<0.05). Large effects were measured at the hip level (about -60%) and a medium-to-large effect was measured at the knee level (about -40%). Peak hip adduction increased in fatigued conditions as well as internal rotation (p<0.05, medium-to-large effect). Hip rotation RoM reduced by 30% (p=0.007). Neither ankle flexion peak nor RoM significantly changed in fatigued conditions (p=0.167 and p=0.431, respectively, small effect).
CoM vertical position significantly increased (5-10%) in fatigued conditions (p=0.004, large effect). While CoM speed at initial contact remained almost unchanged (p=0.656), CoM speed at toe-off significantly dropped (-30%, p=0.001, large effect). Neither side-related differences nor side×condition interactions were observed (p>0.05 for all variables). No significant changes were also observed for the EMG variables (p>0.05), with low ES for both BF and GL.

DISCUSSION: The onset of fatigue during a high-intensity shuttle protocol with repeated 180°-turns progressively induced a substantial reduction of hip and knee flexion, as well as an increase in hip adduction and hip internal rotation. The observed kinematic changes were previously reported to impact on ACL and MCL injury risk (Read et al. 2016).

Ecological validity
The protocol consisted of an intense, mixed aerobic/anaerobic exercise with a high muscular load (average $[La]_b$>10 mM) that recreated the common demands of many disciplines (Ciprandi et al. 2017). Directional changes imply eccentric muscular efforts to decelerate, and the subsequent acceleration elicits fast-twitch fibers and the anaerobic metabolism.

Table 1: kinematics results. Data are presented as mean (standard deviation).

		Fresh condition		Fatigued		partial	
Variable	Parameter	Right	Left	Right	Left	η^2	p
Hip flexion (deg)	peak	32.2 (7.3)	32.6 (7.4)	20.6 (7.5)	20.5 (7.1)	0.285	<0.01
	RoM	18.8 (5.8)	18.2 (5.8)	13.2 (3.7)	14.1 (4.4)	0.100	<0.05
Hip rotation (deg)	peak	20.2 (12.6)	24.5 (14.6)	15.7 (4.7)	18.7 (6.5)	0.106	<0.05
	RoM	30.5 (7.2)	33.8 (6.6)	25.4 (8.0)	27.3 (9.8)	0.123	<0.01
Hip adduction (deg)	peak	10.9 (5.9)	11.7 (4.9)	8.3 (4.1)	9.4 (3.4)	0.092	<0.05
	RoM	10.5 (3.2)	10.9 (3.8)	11.0 (6.5)	11.7 (6.6)	0.003	0.636
Knee flexion (deg)	peak	46.3 (11.1)	47.8 (9.2)	35.6 (11.7)	39.0 (7.7)	0.152	<0.01
	RoM	26.4 (7.4)	27.0 (8.1)	20.8 (4.0)	21.8 (5.7)	0.070	<0.01
Ankle flexion (deg)	peak	8.1 (5.8)	8.4 (5.6)	9.8 (7.9)	12.9 (9.8)	0.027	0.111
	RoM	29.6 (4.8)	28.1 (6.6)	28.9 (5.6)	30.9 (5.8)	0.008	0.800
CoM speed ($m \cdot s^{-1}$)	In. contact	1.49 (0.24)	1.51 (0.36)	1.53 (0.36)	1.56 (0.28)	0.003	0.656
	toe-off	1.50 (0.23)	1.48 (0.26)	1.11 (0.31)	1.23 (0.35)	0.213	<0.01
CoM height (%BH)	min	46.2 (2.6)	46.6 (2.4)	49.2 (2.8)	49.6 (3.2)	0	<0.01

p: fresh vs. fatigued condition, p<0.05. BH: body height.

Fatigue-induced kinematics changes

Peak knee flexion reduced by 30%, and peak hip flexion by 60%. While knee flexion remained above the 30-degrees "safety threshold", it become closer to the so called "position of no-return", in line with previous results on landing or jumping (Read et al. 2016; Weiss & Whatman 2015). When performing cutting tasks, the larger the joint flexion, the more the energy absorbed and the less the load applied to the knee ligaments (Hewett et al. 2016). Thus, a more erected body posture at initial contact was associated with an increased ACL injury risk (Alentorn-Geli et al. 2009).

Hip adduction and internal rotation increased, possibly in an attempt to orient the pelvis towards the new running direction. This could have produced higher rotational moments in the pivoting limb and is potentially harmful for passive structures, that must dissipate the energy that in fresh condition were formerly absorbed by eccentric muscles contraction throughout lower limb flexion. A fatigued muscle tends to absorb less energy (Westerblad et al. 2010).

There were no significant changes in the EMG parameters; median frequency in GL only tended to reduce with fatigue (p=0.07) in GL. Since evidence of a high exercise load during the test was given by values of $[La]_b$ far beyond the aerobic threshold, we hypothesize that turning actions may primarily induce fatigue in muscle groups other than GL and BF, probably in the quadriceps. An imbalance in the hamstrings:quadriceps ratio was proposed to impair knee joint stabilization (Read et al., 2016), and increase strain force on the ACL. However, substantial additional work is required to draw conclusions on EMG data, especially since controversy exists regarding the reliability of surface EMG when dealing with fatigue protocols (Barber-Westin & Noyes 2017).

In summary, we believe that the primary source of the observed kinematic changes was the reduced capability of fatigued muscles to store elastic energy. As a result, knee and hip flexion dropped, producing compensatory adaptations in the coronal and transverse planes at the hip level, and a more upright posture.

Limitations

Results should be considered limited to a male sample. As females suffer from ACL injury 2- to 10-fold more than males involved in the same sports (Hewett et al. 2016), sex-specific injury risk needs to be selectively addressed. The chosen marker-set was a trade-off between the number of markers and reliability of recordings and limited the assessment of knee/ankle to the sagittal plane.

Lastly, the protocol involved repeated pre-planned turns. Although the test recreated team sports activity profiles, during match play turns are unplanned actions and muscles activation strategies can be different from planned turns (Besier et al. 2001).

Table 2: EMG parameters obtained in n=8 participants during the stance phase of the pivoting limb. Median (IQR) values refer to 1st (fresh) vs. 5th (fatigued) minute of exercise.

Muscle	Variable	Unit	Fresh	Fatigued	z-score	p	ES
BF	Median frequency	Hz	78.3 (33.8)	70.5 (23.3)	1.400	0.161	0.350
	RMS	%	17.0 (3.5)	12.5 (6.2)	1.400	0.161	0.350
	Activation time	%	45.0 (8.1)	50.4 (8.6)	1.120	0.263	0.280
GL	Median frequency	Hz	82.0 (18.3)	56.7 (32.7)	1.791	0.073	0.317
	RMS	%	18.3 (7.0)	12.5 (6.0)	0.421	0.674	0.105
	Activation time	%	44.7 (2.7)	46.8 (4.8)	0.700	0.484	0.175

ES: effect size; p: Wilcoxon signed ranks test.

CONCLUSION: Despite these limitations, this study identified kinematic effects of fatigue induced by running with repeated turns, and the findings were both statistically significant and practically meaningful. For trainers and practitioners, being aware of fatigue-induced kinematic modifications is the first step for safe practices management and timely injury prevention. To reduce the risk of non-contact knee injuries, neuromuscular training should be largely discipline-specific. The achievement of a proper sport-specific mechanics has to be emphasized throughout the practice.

REFERENCES

Alentorn-Geli, E. et al., 2009. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surgery, Sports Traumatology, Arthroscopy*, 17(7), pp.705–729.

Barber-Westin, S.D. & Noyes, F.R., 2017. Effect of Fatigue Protocols on Lower Limb Neuromuscular Function and Implications for Anterior Cruciate Ligament Injury Prevention Training. *The American Journal of Sports Medicine*, 45(14), pp.3388–3396.

Besier, T.F. et al., 2001. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Medicine and science in sports and exercise*, 33(3), pp.1176–1181.

Brown, S.R., Brughelli, M., Hume, P.A., 2014. Knee Mechanics During Planned and Unplanned Sidestepping: A Systematic Review and Meta-Analysis. *Sports Medicine*, 44(11), pp.1573–1588.

Chappell, J.D. et al., 2005. Effect of fatigue on knee kinetics and kinematics in stop-jump tasks. *American Journal of Sports Medicine*, 33(7), pp.1022–1029.

Ciprandi, D. et al., 2017. Energy cost of continuous shuttle running: comparison of four measurement methods. *Journal of Strength and Conditioning Research*, in press.

Hewett, T.E. et al., 2016. Mechanisms, prediction, and prevention of ACL injuries: Cut risk with three sharpened and validated tools. *Journal of Orthopaedic Research*, 34(11), pp.1843–1855.

Rafeeuddin, R. et al., 2016. Mapping current research trends on neuromuscular risk factors of non-contact ACL injury. *Physical Therapy in Sport*, 22, pp.101–113.

Read, P.J. et al., 2016. Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in Male Youth Soccer Players. *Sports Medicine*, 46(8), pp.1059–1066.

Weiss, K. & Whatman, C., 2015. Biomechanics Associated with Patellofemoral Pain and ACL Injuries in Sports. *Sports Medicine*, 45(9), pp.1325–1337.

Westerblad, H., Bruton, J.D. & Katz, A., 2010. Skeletal muscle: Energy metabolism, fiber types, fatigue and adaptability. *Experimental Cell Research*, 316(18), pp.3093–3099.