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# Lack of Proprioceptive Strategy Modulation Leads to At-Risk Biomechanics for Anterior Cruciate Ligament in Healthy Athletes

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## ABSTRACT

PICOT, B., M. LEMPEREUR, B. MOREL, N. FORESTIER, and O. RÉMY-NÉRIS. Lack of Proprioceptive Strategy Modulation Leads to At-Risk Biomechanics for Anterior Cruciate Ligament in Healthy Athletes. *Med. Sci. Sports Exerc.*, Vol. 56, No. 5, pp. 942–952, 2024.

**Introduction:** Anterior cruciate ligament (ACL) injuries are frequent in handball, and altered sensory integration may contribute to increased injury risk. Recent evidence showed that proprioceptive postural control strategies differ among athletes. The aim of this study was to evaluate the relationship between proprioceptive strategy and biomechanics during side-cutting maneuvers. **Methods:** A total of 47 handball players performed anticipated and unanticipated cutting tasks. Their postural proprioceptive strategy was then characterized according to the perturbation of the center of pressure displacement generated by the muscle vibration on a firm and foam surface. Individuals able to reweight proprioception from ankle to lumbar signals according to the stability of the support were defined as flexible. Conversely, athletes maintaining an ankle-steered strategy on foam surface were characterized as rigid. Statistical parametric mapping analysis was used to compare pelvic and lower limb side-cutting kinematics, kinetics, and EMG activity from seven muscles 200 ms before and after initial contact (IC) using a two-way ANOVA (group–condition). **Results:** Twenty athletes (11 females and 9 males, 18.5 yr) were characterized as flexible and 20 athletes (12 females and 8 males, 18.9 yr) as rigid. No interaction between condition and proprioceptive profile was observed. More ipsilateral pelvic tilt before IC and lower vastus lateralis (VL) activity immediately after IC was observed during CUT<sub>ant</sub>. When comparing proprioceptive strategy, rigid individuals exhibited less preactivity of the semitendinosus ( $P < 0.001$ ) and higher VL activity ( $P = 0.032$ ). Conversely, rigid showed higher gluteus medius preactivity ( $P < 0.05$ ) and higher VL activity 100 ms after IC ( $P < 0.001$ ). Ankle was also more internally rotated before and during the stance phase ( $P < 0.05$ ) among rigid athletes. **Conclusions:** Rigid handball players exhibited at-risk determinants for anterior cruciate ligament injuries during side-cutting maneuvers. **Key Words:** SENSORY INTEGRATION, HANDBALL, CENTRAL RISK FACTORS, PROPRIOCEPTIVE REWEIGHTING, SENSORIMOTOR CONTROL, INJURIES

Anterior cruciate ligament (ACL) injuries are frequent in handball that is considered one of the highest risk sports, with 1%–4% of players sustaining an ACL injury every year (1). Young athletes are more likely to sustain injury, particularly during side-cutting maneuvers, which is the most common injury situation in handball (2,3). Because movement technique directly affects the knee joint loading, numerous studies aimed to identify biomechanical and neuromuscular determinants associated with higher risk factor for

ACL injuries (2,4). For example, lower preactivity of the hamstring and higher quadriceps recruitment (quadriceps dominant strategy) during the stance phase increased the risk of ACL injury among handball players (2,5). Similarly, trunk/pelvic orientation and foot kinematic could directly influence the risk of ACL injury (4). Greater trunk and pelvic contralateral inclination (i.e., relative to the direction of movement) as well as increased internal rotation of the foot during stance phase increase knee abduction moments and are therefore considered as potential risk factors for further injury (6–8).

Most injury prevention programs are designed to train and target these determinants and improve neuromuscular control during landing or side-cutting maneuvers (9). However, despite their implementation, the rate of ACL injuries has continued to rise over the past 20 yr, and recent evidence pointed out central nervous system alterations as important risk factors (10–13).

Yet, neurocognitive and neurophysiological impairments contribute to motor control error, especially during high cognitive constraints such as dual task situations (14,15). Central

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alterations may thus be responsible for sensorimotor mismatch leading to mechanical instability of the knee joint (10,11). Individuals with high-risk landing biomechanics for ACL injuries exhibited more structured, less variable, cortical activity in frontal and parietal brain regions, suggesting that less adaptive brain activity may relate to poor sensorimotor control (16).

During game situations, the unpredictability of player environment's may produce high cognitive demand that could compromise knee stability during complex motor tasks (14,15). It has been shown that unanticipated cutting maneuvers produce higher constraints on the knee joint, in particular greater knee abduction and tibial internal rotation moments, that could further lead to ACL injury (17). As a result, the overall incidence rate in handball is 20 times higher during matches compared with training sessions (18). Two prospective studies have identified decreased brain functional connectivity between cortical sensory and motor regions before ACL injuries (10,11). This altered connectivity may lead to an inability to react to environmental changes such as opponent behavior during dual tasks (15,19). Interestingly, alterations in brain regions responsible for proprioceptive reweighting have been reported after ACL injuries (20–22) and could further explain the risk of recurrences.

It seems therefore necessary to evaluate relationships between proprioceptive reweighting and motor pattern (i.e., biomechanical control and neuromuscular firing patterns) during unplanned situations. Indeed, during those complex situations, proprioceptive reweighting (the process by which the CNS dynamically adjusts the weight assigned to proprioceptive signals) becomes crucial to ensure performance and proper knee stability (14).

The term “proprioceptive control strategy” refers to how an individual integrates proprioceptive signals to control their motor actions (23). The ability to reweight proprioceptive signals from one anatomical region to another (intramodal reweighting) allows for flexibility in individual's motor control (24). A lack of proprioceptive control strategy modulation (i.e., proprioceptive reweighting) could potentially be linked with at-risk biomechanics behaviors because it reflects an inability to adapt to external stimuli and to select the most reliable somesthetic signals at a given time/condition (25,26). Recent evidence revealed discrepancies in the capability to reweight proprioceptive signals during postural tasks among healthy athletes (23). Two opposing behaviors have been identified. First, a “flexible” strategy that involved a proprioceptive reweighting from ankle to lumbar proprioception when standing on foam surface. Conversely, “rigid” individuals used an ankle-steered strategy regardless of balance conditions (23,26). This lack of proprioceptive flexibility was associated with sub-optimal postural strategy, with rigid individuals showing less ability to recover their stability after balance perturbation and exhibiting aberrant recruitment (i.e., overactivation) of the hamstrings during the restabilization period (23). Because it is now well established that balance control and hamstring activity are important risk factors for ACL injuries (2,5,27),

it appears relevant to deepen the link between proprioceptive flexibility and motor control during complex tasks in handball.

Based on previous results from Picot et al. (23) on hamstrings recruitment, the objective of this study was therefore to evaluate the relationship between proprioceptive postural strategies and biomechanical determinants associated with increased risk of ACL injuries during handball-specific cutting maneuvers. More specifically, we aimed to assess muscle preactivation and biomechanical known determinants to increase the risk for ACL injury. It has been hypothesized that young athletes unable to reweight proprioceptive signals (i.e., rigid individuals) exhibit low level of hamstring preactivity. Similarly, differences in trunk/pelvic lateral inclination and foot position during the stance phase were expected between the two groups.

To our knowledge, no previous studies have investigated both neuromuscular control and lower limb biomechanics of handball players between planned and unplanned situations. Thus, the secondary aim of this study was to compare kinematics, kinetics, and muscle activation between anticipated and unanticipated handball-specific cutting maneuvers. Based on results from other sports, it was hypothesized that unanticipated tasks induce biomechanical determinants associated with an increased risk of ACL injuries such as increased pelvic/trunk contralateral inclination or quadriceps overactivity during stance phase.

Finally, as proprioceptive reweighting reflects the capacity of the CNS to adapt to a change in environment, the third objective of this study was to evaluate the interaction between proprioceptive profile (i.e., rigid vs flexible) and cutting condition (anticipated vs unanticipated). It was hypothesized that rigid athletes would have more biomechanical determinants associated with the risk of ACL rupture in unanticipated situations.

## METHODS

### Ethical Approval

According to the French law, an institutional review board was randomly selected and approved the protocol (CPP Ouest IV, Nantes, 02/21\_2). Written informed consent, which conformed to the Declaration of Helsinki, was obtained from each participant (or legal tutors). Full details of the study design and experimental procedures were registered before subject recruitment on clinicaltrials.gov (NCT04736511).

### Participants

Based on previous results (23,28), *a priori* calculation of the number of subjects required to obtain a statistical power of 0.80 and type 1 error of 0.05 showed that at least 39 subjects were needed. Inclusion criteria were high-level handball players aged between 15 and 25 yr. Only athletes familiar with side-cutting maneuvers (i.e., back or wing players) with at least 2 yr of experience at high level and a minimum of 5 h of training per week were included. Exclusion criteria were

known neurological disorders, vestibular impairment, and trunk or lower limb injuries within the previous 3 months.

## Procedure

A single measurement session was organized for a total duration of approximately 2 h 30 min per subject. The athlete performed a 15-min standardized warm-up consisting of 5 min of cycling at  $2 \text{ W} \cdot \text{kg}^{-1}$  of body mass, followed by 10 squats on each leg, then 5 hops at high intensity, and finally 5 bipodal counter movement jumps at maximum intensity.

**Side-cutting maneuvers.** Participants were asked to run in a straight line for 5 m and then either to perform a side-cutting maneuver as fast as possible on their dominant limb (i.e., preferred push-off leg) (29) or continue in a straight line (Fig. 1). During the run-up, the subject crossed photoelectric cells designed to measure approach speed and trigger a visual signal 600 ms before contacting the platform (30). To normalize the onset time of the visual signal, the lighting delay was calculated for each participant based on its approach speed during the 10 familiarization trials (31). A green visual signal indicated to the player to continue running in a straight line, whereas a red visual signal forced him to perform the cut. All participants first performed three anticipated side-cutting maneuvers ( $\text{CUT}_{\text{ant}}$ ) where the experimenter previously indicated which color will light-up. In the second stage, 10 unanticipated trials were randomly performed with five cutting situations ( $\text{CUT}_{\text{unant}}$ ) and five straight-line runs (2,6,32). Approximately 30 s of rest were allowed between each trial, and participants could start the next trial as soon as they felt ready. The average of the three anticipated and five unanticipated cut were calculated for each participant.

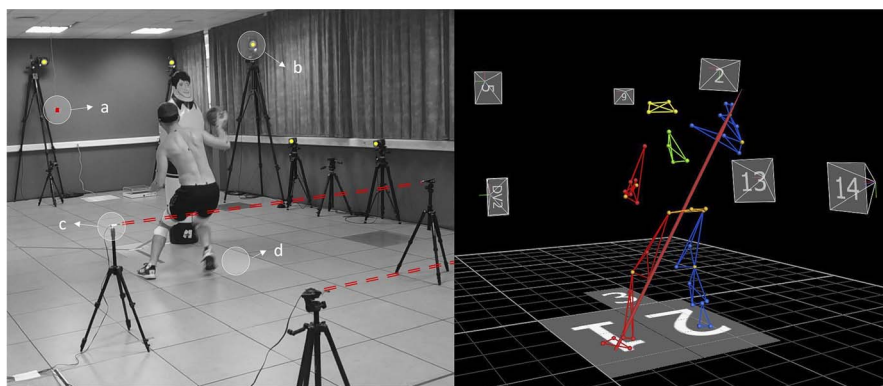
Although only the side-cutting tasks ( $\text{CUT}_{\text{ant}}$  and  $\text{CUT}_{\text{unant}}$ ) trials were analyzed, the straight run served to prevent the participants from anticipating the type of maneuver. Both straight-line running and cutting tasks mimic handball situations where, depending on opponent behavior, the attacker must fake and outflank the defender or cross the defensive line to shoot. To best reproduce game situations, participants had to fake a simulated defender (i.e., 185 cm high training dummy) placed 1 m behind the force platform while carrying a ball

(33). Neither the change-of-direction angle nor the approach speed was imposed (2). The run-up allowed players to achieve an approach speed comparable with those found in matches (between  $3$  and  $4.5 \text{ m} \cdot \text{s}^{-1}$ ). The reliability of this procedure was shown to be excellent among handball players (5,32).

**Postural tasks.** To dichotomized participants according to their proprioceptive strategy (i.e., flexible vs rigid), the same procedure previously described was used to ensure proper reliability (23,34). Participants stood barefoot in bipedal stance with their arms relaxed by their sides and their head in neutral orientation. Foot position was standardized, and vision was prevented using opaque goggles. Two postural conditions were randomly evaluated: “firm” (standing on the force platform) and “foam” (Physiopad®;  $50 \times 41 \times 5 \text{ cm}$ ;  $52 \text{ kg} \cdot \text{m}^{-3}$ ). Four muscle vibrators (VB115, Techno Concept, France) set at 80 Hz with an amplitude of 0.5 mm were randomly triggered to bilaterally stimulate muscle spindles of the triceps surae (TS) or the lumbar paravertebral muscles (LPM). For the TS, each vibrator was placed on the Achilles tendon, about two fingers above the lateral malleolus, and on the muscle bellies on either side of the lumbar spine between the posterior–superior iliac spines for the LPM. Each trial lasted for 50 s. Recordings began 10 s before vibration (“PRE”), vibration was then applied for 20 s (“VIB”), and the recording continued for another 20 s during the restabilization period (“POST”). The level of fatigue was assessed using a Borg scale and heart rate at the beginning of the testing session and before the side-cutting and posture tasks to limit the bias of comparisons between individuals.

## Electrodes and Markers Placement

EMG activity from the gluteus medius (GM), biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), and fibularis longus (FL) was recorded by bipolar surface electrodes (Trigno Wireless; Delsys Inc., Natick, MA). Those muscles were chosen based on their involvement in the context of ACL rupture (2,35,36). Before electrodes placement, subjects’ skin around the recording sites was shaved and cleaned to reduce skin impedance. Electrodes were placed by the same experimenter according to the Surface



**FIGURE 1**—Illustration of the experimental setup (*left*) visual signal (A), infrared camera (B), photoelectric cell (C), force plates (D) and resulting biomechanical model used for lower limb kinetic and kinematic calculations (*right*).

EMG for the Non-Invasive Assessment of Muscles (SENIAM) guidelines to ensure proper reliability (37). EMG signals were normalized to the peak amplitude obtained during the CUT<sub>ant</sub> condition. This method showed higher reliability than the normalizations to isometric voluntary maximum contraction in handball overrun maneuvers (5).

Each subject was also equipped with 48 infrared markers distributed over the head ( $n = 4$ ), trunk ( $n = 4$ ), at the spinous processes of C7 and T8, the jugular incisure and the xiphoid process of the sternum. For the upper limbs, the markers ( $n = 9$ ) were located on the acromion, the lateral and medial epicondyles of the humerus, the radial and ulnar styloid processes, the heads of the metacarpals 2 and 5, and two markers on the upper arm and forearm. For the lower limbs, the markers ( $n = 11$ ) were placed on the anterior and posterior–superior iliac spines, the medial and lateral epicondyles of the femur, the medial and lateral malleoli, the heel and the heads of the metatarsals 1 and 5, as well as on the thigh and leg segments. Markers and electrodes were secured with Hypafix® and then fixed with circular tapes to limit the movement during dynamic tasks.

## Data Analysis

**Side-cutting maneuver.** A three-dimensional (3D) analysis system consisting of 15 infrared cameras (Vicon Oxford Metrics, UK) with a sampling rate of 100 Hz synchronized with two embedded platforms (1000 Hz; AMTI, Watertown, MA) were used to calculate knee kinetics (frontal, sagittal and transverse internal moments), kinematics of the hip, knee, ankle (flexion, abduction, and rotation), trunk (flexion, lateral flexion and rotation), and pelvis motions (flexion, lateral tilt, and rotation) during cutting maneuvers (38). Rotation and lateral inclination (ipsi- or contralateral) of the pelvis and the trunk were relative to direction of movement (4,8).

EMG signals were collected at a sampling rate of 1000 Hz, filtered with a bandwidth of 20–450 Hz, and then rectified. The envelope of the EMG signal was then obtained for each trial from a low-pass filter (second-order Butterworth; cutoff frequency, 10 Hz). ACL injuries are likely to occur within the first 100 ms of the contact phase (3); however, muscle preactivity as well as lower limb kinematics before initial contact (IC) highly influence the risk of injury (2,4). All data were synchronized and analyzed on a window from 200 ms before and 200 ms after the IC. EMG signals were then normalized to the peak amplitude obtained during the anticipated condition (5).

**Postural tasks.** A force platform (1000 Hz, AMTI) was used to record the center of pressure displacement ( $dCoP$ ). Signals were stored and filtered using a Butterworth low-pass, fourth-order filter with a cutoff frequency of 10 Hz. The relative proprioceptive weighting ( $dRP_W$ ) was then calculated for each participant on firm and foam surface. This value is defined as the ratio between the effects of the vibration of the TS and the LPM on absolute anterior–posterior  $dCoP$ . It provides a reliable indication of individual proprioceptive strategies (23,34):

$$dRP_W = \frac{\text{abs } dCoP_{TS}}{[\text{abs } dCoP_{TS} + \text{abs } dCoP_{LPM}]}$$

The change in the  $dRP_W$  between firm and foam support (expressed as a percentage of the  $dRP_W$  on firm support) was used to dichotomize participants according to their ability to reallocate their proprioceptive dominance on each support. Contrary to Picot et al. (23) who used a cutoff value of 100% to characterized proprioceptive flexibility, in this study, a change  $\leq 95\%$  corresponded to a reallocation of signals from ankle to lumbar and reflected a flexible proprioceptive strategy. Conversely, a change  $\geq 105\%$  indicated a rigid profile associated with a lack of proprioceptive flexibility traducing an ankle-steered strategy (25,26). This method was chosen to avoid incorrect characterization of participants due to the variability of this index (34). Consequently, participants with a change of  $dRP_W$  value comprised between 95% and 105% were not characterized.

## Statistical Analysis

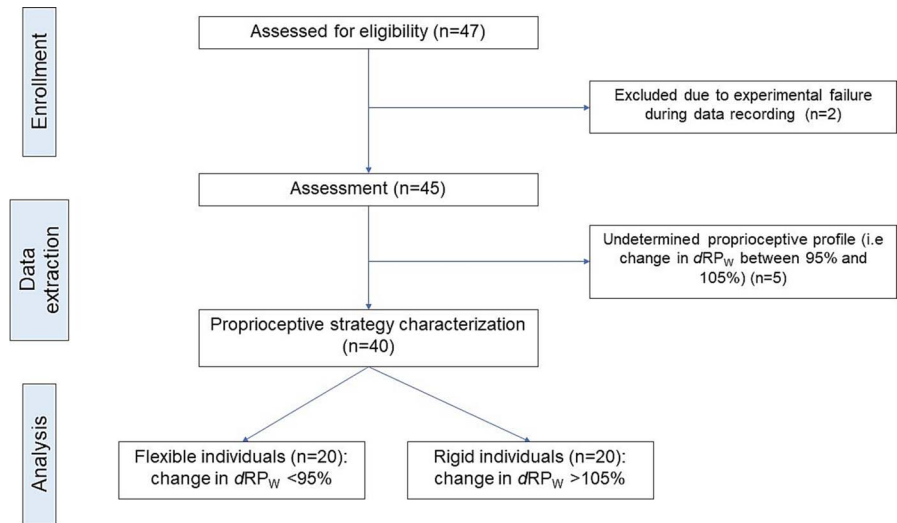
Normality was assessed using the Shapiro–Wilk test. Approach speeds were compared between CUT<sub>ant</sub> and CUT<sub>unant</sub> as well as between rigid and flexible participants using paired (condition) and independent (proprioceptive strategy) *t*-test. A 2-way ANOVA SPM $\{F^*\}$  statistics was performed to determine the main effects of proprioceptive strategy (rigid vs flexible) and condition (anticipated vs nonanticipated) as well as the interactions between these factors on kinetic, kinematic, and EMG time series. After vector field analyses, *post hoc* two-sample SPM $\{t\}$  (2-sided) were conducted on each vector component separately with *t* tests. A *P* value with Bonferroni correction was calculated for each cluster crossing the critical threshold, with statistical significance set at  $\alpha = 0.05$  (39).

All analysis were performed on SPSS software (IBM, Chicago, IL) and SPM-1D software (© Todd Pataky, 2014, version M0.1) (39) on Matlab (R2013b; The Mathworks Inc., Natick, MA).

## RESULTS

Based on the dichotomization method, 40 of the 47 participants (23 women and 17 men,  $18.6 \pm 2.2$  yr old) were finally classified, whereas 7 participants (14% of the sample) were not analyzed. This resulted in the identification of 20 flexible and 20 rigid individuals (Fig. 2). Rigid athletes showed significant higher change in  $dRP_W$  than flexible individuals ( $119.0\% \pm 21.2\%$ , vs  $72.3\% \pm 10.9\%$ ;  $P < 0.001$ ) (Table 1). No difference was found in approach speed between the two groups.

Between-group comparisons revealed less preactivity of the ST ( $F^* = 7.01$ ,  $P < 0.001$ ) and VL ( $F^* = 6.79$ ,  $P < 0.05$ ) from 200 to 100 ms before IC in rigid individuals (Fig. 3). Conversely, they showed greater GM preactivity ( $F^* = 6.98$ ,  $P < 0.05$ ) and ankle internal rotation 200 ms before IC ( $F^* = 6.745$ ,  $P < 0.05$ ) (Figs. 3 and 4). At 70 ms after IC, higher VL activity ( $F^* = 6.79$ ,  $P < 0.001$ ) and higher ankle internal rotation ( $F^* = 6.745$ ,  $P < 0.05$ ) were also observed



**FIGURE 2—Flowchart of inclusion and analysis processes.**

among rigid players. No other differences were observed for kinematics, kinetics (Fig. 5), or EMG variables between the two groups.

When comparing data between anticipated and unanticipated tasks in the overall population, results revealed that during CUT<sub>unant</sub>, athletes showed less ipsilateral pelvic tilt before IC ( $F^* = 6.623, P < 0.05$ ) (Fig. 6 and 7) as well as higher VL activity 50 ms after IC ( $F^* = 6.79, P < 0.05$ ) (Fig. 6). No other differences were observed for kinematic, kinetic (Fig. 5), or EMG variables between the two conditions.

Lastly, no interaction was found between proprioceptive strategy (flexible vs rigid) and conditions (CUT<sub>ant</sub> vs CUT<sub>unant</sub>) in kinematics, kinetic, or EMG activity.

**DISCUSSION**

The main objective of this study was to evaluate the relationship between proprioceptive postural strategies and biomechanics previously associated with the risk of ACL injuries during handball-specific side-cutting maneuvers. The secondary aim was to compare anticipated and unanticipated side-cutting maneuvers and then to evaluate the interaction between proprioceptive profile (i.e., rigid vs flexible) and cutting condition (CUT<sub>ant</sub> vs CUT<sub>unant</sub>).

TABLE 1. Baseline population characteristics.

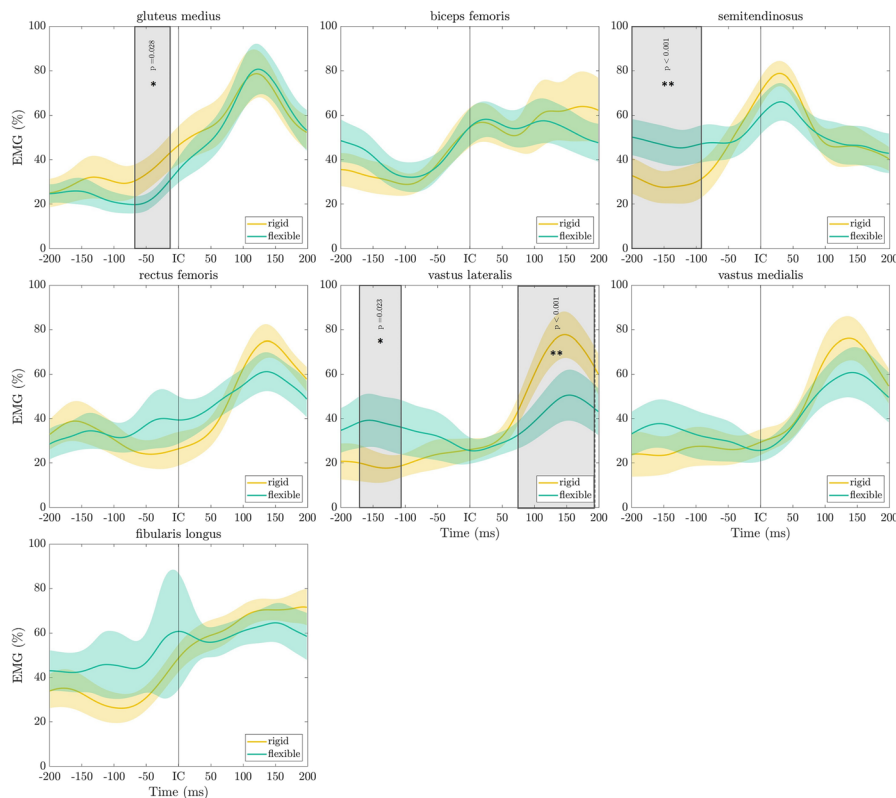
Variables	Proprioceptive Strategy		P
	Flexible (n = 20)	Rigid (n = 20)	
Females/males	11/9	12/8	0.749
Size (m)	1.73 ± 0.1	1.71 ± 0.1	0.601
Mass (kg)	69.4 ± 9.7	65.8 ± 10.3	0.262
Body mass index	23.2 ± 2.3	22.3 ± 2.4	0.244
dRP <sub>w</sub> on firm surface	0.85 ± 0.1	0.7 ± 0.2	0.004
dRP <sub>w</sub> on foam surface	0.61 ± 0.1	0.82 ± 0.1	<0.001
Change in the dRP <sub>w</sub> (%)	72.3 ± 10.9	119.9 ± 21.2	<0.001
Age (yr)	18.5 ± 2.5	18.9 ± 2.3	0.595
Approach speed (m·s <sup>-1</sup> )	3.43 ± 0.33	3.37 ± 0.33	0.571

Data are shown as mean ± SD. dRP<sub>w</sub>, relative proprioceptive weighting calculated from the center of pressure displacement.

The first important result is the confirmation of a high degree of variability in proprioceptive reweighting capacities among handball players (23). Indeed, the data support the results showing two opposite proprioceptive postural strategies in a population of young healthy handball players. Rigid individuals exhibit lower EMG activity of the ST before IC, which has been previously associated with increased ACL injury risk in handball players (2,5). Indeed, those muscles play an important role in the sagittal plane by counteracting anterior translation of the tibia that lead to an ACL anterior shear (40). Moreover, in the frontal plane, medial hamstring recruitment is a key contributor of knee adduction and lead to compression of the medial knee joint compartment. The higher level of ST preactivity observed in flexible athletes may serve an antagonistic role to external knee abduction (2) that is considered as major risk factor for ACL injury (41). Interestingly, several studies showed an increased preactivity of the ST after an injury prevention program and highlighted the role of hamstring recruitment before IC in the context of ACL prevention (42,43).

Conversely, higher recruitment of the VL was observed among rigid individuals within the first 100 ms of the stance phase. An exacerbated activity of the quadriceps shortly after IC could lead to increase anterior shear forces and contributes to excessive ACL strains (35,40,44). Because rigid athletes combined a reduce level of hamstring muscle preactivation and a higher VL recruitment, it further provides less protective capacity for ACL unloading (35,40,44).

Higher preactivity of the GM was also observed among rigid athletes. Although the role of hip abductor and external rotator strength is crucial in the context of ACL injury (45), proper muscle activation is needed to control frontal plane movements of the knee. However, the meta-analysis from Cronström et al. (46) did not revealed association between GM activity and injury risk. Recent results confirmed the absence of correlation between maximal hip abductor force and GM preactivity during side-cutting maneuver (47). Homan et al. (48) revealed that groups with low strength in abduction and external rotation



**FIGURE 3**—EMG activity (% of the peak amplitude obtained during the anticipated condition) of the gluteus medius (GM), biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), and fibularis longus (FL) among flexible (*green*) and rigid (*yellow*) athletes recorded during side-cutting maneuver. The vertical line corresponds to the IC. The data for the two conditions (anticipated and nonanticipated) are pooled.

displayed relatively higher EMG amplitudes compared with the high strength groups. It could be argued that athletes with weaker hip abductors would demonstrated greater EMG amplitudes (49), and high GM activation seems to be not beneficial during cutting tasks. Indeed, injury prevention programs that show decreased incidence rate of ACL injury also lead to a decreased preactivation of the GM (43,50).

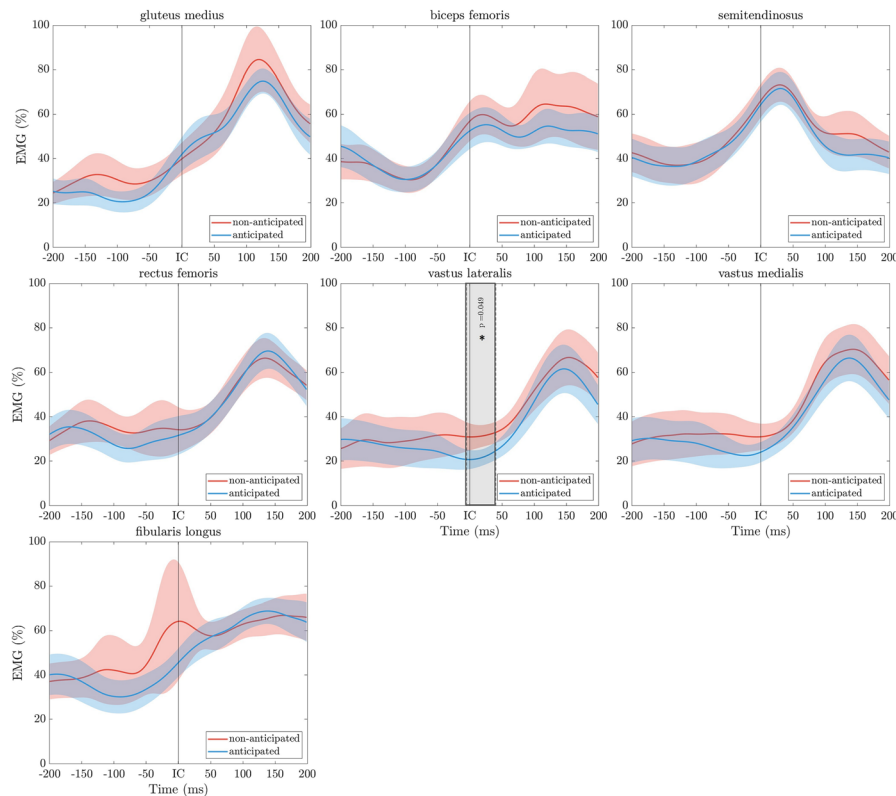
Rigid individuals also exhibit higher internal rotation of the ankle before and 75 ms after IC (which corresponds to the estimated time of injury). Increased internal rotation during stance phase is now considered as an important risk factor for ACL injuries (4). Subjects with excessive valgus moments during a side-step cutting maneuver demonstrated an initial loading pattern that included more internally rotated foot progression angle compared with the group exhibiting normal moment in the frontal plane (51). Recent data also revealed that internal rotation of the foot ( $-12.6^\circ$ ) could lead to an increased risk of ACL injury during a preplanned side-cutting maneuver, compared with a neutral foot position or lateral rotation ( $2.3^\circ$  and  $19.5^\circ$  respectively) (7). At IC, flexible individuals placed their foot in a slight external position ( $2.3^\circ$ ), whereas rigid athletes were already in internal rotation ( $-1.6^\circ$ ) (Fig. 4). It is interesting to note that the internal rotation amplitude observed in rigid athletes during the first milliseconds after IC is very similar to that reported in ACL lesions ( $-6.9^\circ$  and  $-7^\circ$  in the first 40 ms respectively) (52) and greater than in flexible individuals ( $<5^\circ$ ). In

addition, 75 ms after IC, ankle internal rotation was significantly higher among rigid athletes than in flexible athletes ( $-8.49^\circ$  vs  $-3.17^\circ$ ). The combination of higher quadriceps recruitment and internal rotation of the tibia during the deceleration and acceleration phases of side-cutting could lead to excessive load on the ACL (17). This was observed among rigid athletes around 75 ms after IC (Figs. 3 and 4), which corresponds to the estimated time of injury (3). The overall results revealed that young handball players showing lack of proprioceptive flexibility exhibit kinematics and neuromuscular control of the stance limb that could lead to an increased risk of ACL injury during side-cutting maneuver.

It therefore seems appropriate to implement a targeted neuromuscular prevention program to modify knee joint motor control during side-cutting in rigid individuals (43,53). For instance, EMG preactivity of the ST was selectively increased during side-cutting maneuvers after the implementation of kettlebell swing exercises (54,55). In addition, it might be relevant to propose a change of the cutting technique among rigid individuals (56). Instructions to keep the ankle in neutral rotation during the stance phase appear to be particularly effective in reducing loads on the ACL (7,57,58).

However, despite these significant differences, knee joint moments and kinematics were similar between rigid and flexible individuals (Fig. 5). This could be explained by the fact that knee moments are influenced by several components of





**FIGURE 6**—EMG activity (% of the peak amplitude recorded during the anticipated condition) of the gluteus medius (GM), biceps femoris (BF), semitendinosus (ST), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), and fibularis longus (FL) during anticipated (*blue*) and unanticipated (*red*) cutting maneuver. The vertical line corresponds to the IC. The results represent the entire sample (i.e., data from rigid and flexible individuals are pooled).

the cutting technique (4,6). External moments calculated here are not representative of the specific action of the muscles but of all the kinetic constraints applied to the joint. Recent evidence have also shown no direct association between knee joint moments and the risk of ACL injury (2).

The second objective of this study was to compare anticipated and unanticipated side-cutting maneuvers. To our knowledge, this is the first study evaluating both kinematics, kinetic, and neuromuscular control during unanticipated handball-specific tasks. The greater ipsilateral pelvic tilt observed before IC during planned situations reflects a postural adjustment to preorient the center of mass in the new direction (Fig. 7). Higher ipsilateral pelvic tilt during anticipated side-cutting has been previously observed (4,8) and contributes to reduced ACL loading (4,17,59).

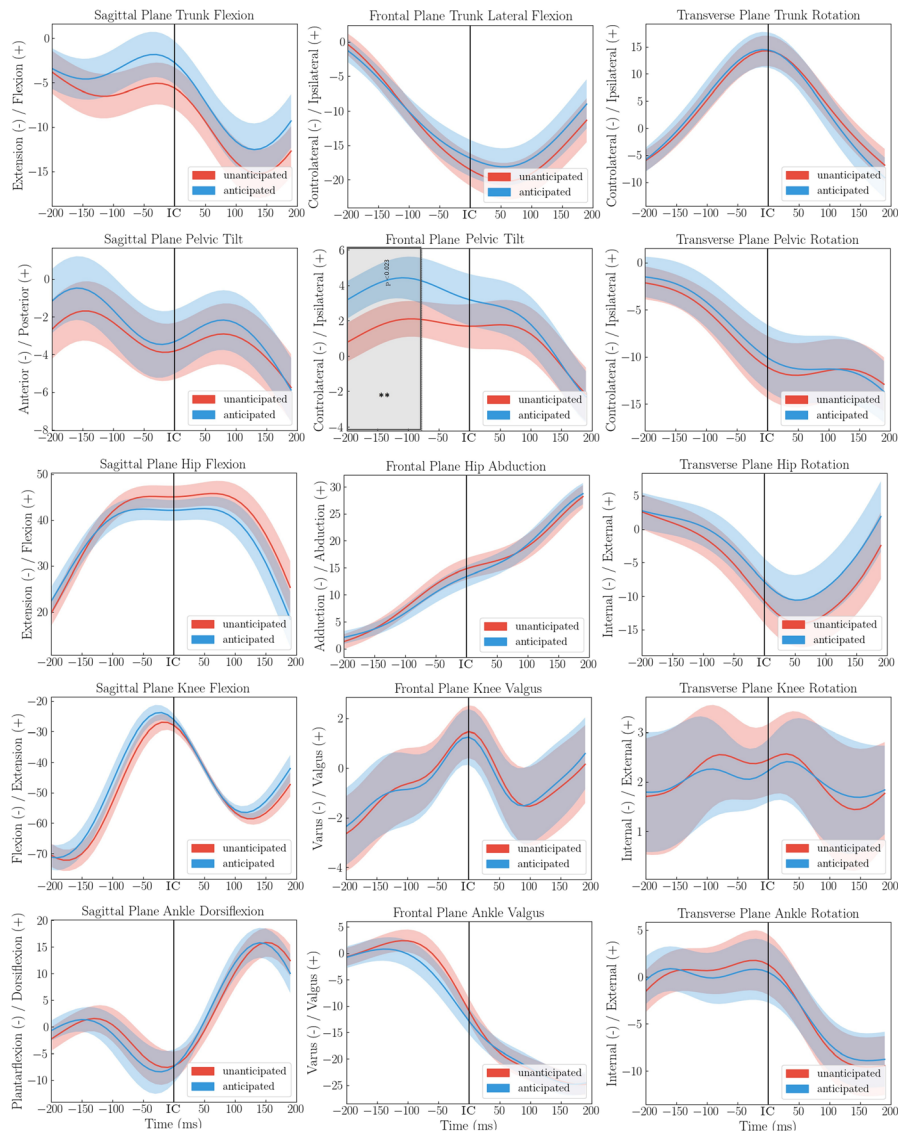
During unplanned tasks, more VL activity 50 ms after IC was also observed (Fig. 6). This could be explained by a need to rapidly decelerate and reorient the center of mass (44). Higher quadriceps recruitment during this phase could increase anterior tibial shear forces in cases of inadequate hamstrings coactivation and might therefore be associated with higher risk of ACL rupture (35,40,44). It is important to note that this overactivation occurs at the time of maximum knee abduction (40 ms) that corresponds to the assumed time of injury (Fig. 5).

The combination of reduced pelvic tilt and increased quadriceps activity reflects neuromotor behavior that increases

stress on the ACL (4,6,8,35) and tends to confirm the influence of unanticipated tasks on the ACL injury risk (17). However, these EMG and kinematic modifications do not have a measurable effect on knee moments because no difference was observed between the two conditions (Fig. 5).

Controversial results exist when comparing knee moments during planned and unplanned conditions. In contrast to previous systematic reviews (17),  $CUT_{unant}$  did not lead to higher knee moments (Fig. 5). However, these results are in accordance with a recent study among young handball players showing no increase in knee abduction moment during unanticipated side-cutting maneuvers (60). According to the authors, elite handball players have developed an automated motor program throughout their careers, which is used for both planned and unplanned tasks. This could also explain the absence of interaction between the proprioceptive profile of the athletes and the anticipatory nature of the task in our study. Indeed, results from Mai et al. (60) showed strong correlations between tasks, indicating that cutting technique and joint loading are unique and depend on each player's motor program. It could be speculated that rigid individual exhibits at-risk kinematic and neuromuscular control regardless the complexity of the tasks.

Several studies have previously identified association between functional connectivity of brain regions responsible for proprioceptive integration and high ACL injury risk



**FIGURE 7—Kinematics (°) of the trunk, pelvis, hip, knee, and ankle recorded during anticipated (blue) and unanticipated (red) cutting maneuver. The vertical line corresponds to the IC. The results represent the entire sample (i.e., data from rigid and flexible individuals are pooled).**

biomechanics (16,61). It would be relevant to compare rigid and flexible individuals using neuroimaging to better understand which brain regions are involved in proprioceptive flexibility and their implications on biomechanical organization during motor tasks.

To our knowledge, this is the first study identifying the association between individual’s proprioceptive profile (afferences) and motor program (efferences) during gamelike situations in the context of ACL injury. However, although the procedure aimed to reproduce real game situations, these are still so-called laboratory tasks, different from real match environmental constraints (62). To confirm the influence of proprioceptive postural strategy on ACL rupture, prospective studies are needed to compare the incidence of these injuries between rigid and flexible individuals.

Furthermore, we have only examined EMG activity, and its interpretation is not equivalent to the force produced by the

muscle. The normalization procedure may have flaws, such as higher activation for weaker muscles. Given that EMG activity and muscle strength are predictive of ACL injury, further studies are needed to compare muscle strength among flexible and rigid individuals. Lastly, there was an artificial attrition of 14% of the subjects based on arbitrary cutoff values defining the two groups. Further studies are needed to assess the biomechanical and neuromuscular behavior of this third group (i.e., those who retained the same RPW on both surface).

Lastly, in this study, we only examined the dominant limb of athletes (2). In handball, cutting maneuver is a fundamental movement pattern frequently used in training sessions where athletes mostly exhibit a preferred side, allowing them to shoot with their dominant arm (5,32). For example, a right-handed athlete typically feints and moves to the right, using their left leg (so-called the dominant one). A critical limitation in many studies assessing side-cutting maneuvers is the definition of

limb dominance as the preferred kicking limb (63). Authors of this systematic review recommend to evaluate athletes in sports like handball, basketball, netball, and rugby by considering their preferred turning (push-off) limb, as kicking is not a regularly performed action in these sports. Nevertheless, several studies have compared the dominant versus nondominant limb biomechanics in handball and shown no significant differences between both legs (29,32).

## CONCLUSIONS

Proprioceptive postural control strategies influence biomechanics and neuromuscular activity during side-cutting maneuvers. Individuals showing less proprioceptive flexibility exhibit several determinants previously associated with an increased risk of ACL injury. Rigid athletes showed less medial hamstring preactivity associated with an increased recruitment of the VL after IC. They also revealed a more internally rotated ankle position during the stance phase. During unplanned situations, athletes

also exhibit less ipsilateral pelvic tilt before IC and higher quadriceps activity during the stance phase that could increase ligament constraint. Further prospective studies are needed to confirm the role of proprioceptive flexibility and the risk of ACL injury during side-cutting maneuvers. In particular, experimental conditions closer to real match conditions could provide a better understanding of the influence of biomechanical markers on the risk of ACL injury.

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