



Motor imagery in high-functioning individuals with chronic anterior cruciate ligament deficiency: A cross-sectional study

Shiek Abdullah Ismail^{a,*}, Milena Simic^a, Tasha R. Stanton^{b,c}, Evangelos Pappas^a

^a Discipline of Physiotherapy, Faculty of Health Sciences, The University of Sydney, Sydney, Australia

^b School of Health Sciences, The University of South Australia, Adelaide, Australia

^c Neuroscience Research Australia, Sydney, Australia

ARTICLE INFO

Article history:

Received 21 June 2018

Received in revised form 1 February 2019

Accepted 22 February 2019

Keywords:

Left/right judgement

Motor imagery

ACL

Accuracy

Reaction time

Spatial representation

ACL deficient

Knee

ABSTRACT

Background: There is increasing evidence that motor imagery performance (MIP) is impaired in conditions that have a component of movement dysfunction. However, MIP has not been investigated in people with chronic anterior cruciate ligament (ACL) deficiency who experience limited disability and function at high levels.

Hypothesis: This study had three objectives: (1) to assess implicit MIP in individuals with a chronic ACL deficient (ACLD) knee compared with healthy controls (i.e., intact anterior cruciate ligament); (2) to determine if the location of ACL deficiency affects MIP (dominant versus non-dominant leg); and (3) to determine if impairment in MIP is specific to the side (injured versus non-injured) of ACL deficiency.

Methods: Forty-five participants with chronic ACLD knee and 44 healthy controls completed a left/right judgement task of pictured knees using the “Recognise” app to evaluate implicit MIP. Accuracy and reaction time of judgements were compared between groups. Additionally, within the chronic ACLD knee group, we made comparisons between the dominant ACLD knee and non-dominant ACLD knee subgroups and between the injured knee and the non-injured knee of the ACLD group.

Results: There were no differences in implicit MIP between the ACLD knee and the control group, the non-injured knee versus injured knee of the ACLD knee group, or the dominant ACLD knee versus non-dominant ACLD knee subgroups.

Conclusion: Implicit MIP is not disrupted in high functioning individuals with chronic ACLD knee.

© 2019 Elsevier B.V. All rights reserved.

1. Introduction

Anterior cruciate ligament (ACL) rupture is one of the most devastating knee injuries that frequently affects active and young individuals [1,2]. Although motor impairment could be a result of mechanical instability after ACL injury [3], proprioceptive deficits in the knee joint have also been proposed to contribute to the motor impairment associated with ACL deficiency [4–6]. The ACL contains mechanoreceptors which inform the central nervous system (CNS) about joint sense position and kinaesthesia [7,8].

* Corresponding author at: Discipline of Physiotherapy, Faculty of Health Sciences, The University of Sydney, Cumberland Campus C42, 75 East Street, Lidcombe, NSW 2141, Australia.

E-mail address: shie1497@uni.sydney.edu.au (S.A. Ismail).

Proprioception of the knee is influenced by the integration of afferent signals from these receptors and other proprioceptive receptors found in different knee structures [6,9,10]. Thus, rupturing the ACL will partially disrupt the ascending afferent pathway towards CNS [7,11–13]. Indeed, there is now evidence demonstrating changes in the CNS occurring after ACL injury [12–14]. For example, individuals with ACL-deficient (ACLD) knee demonstrate decreased cortical activation when compared with healthy participants during activation of fibres subserving the ACL [14]. Additionally, two neuroimaging studies that measured cortical activation during knee flexion-extension task among individuals who had ACL injuries and in matched healthy controls found that cortical activation is altered among the individuals with ACL injuries [12,13].

While previous work supports the conceptual framework of neuroplasticity changes after ACL injury, it is unknown whether or how the decreased innervation to the primary sensorimotor area impacts the integrity of the body schema [15]. The internal cortical maps which the brain uses for movement depend on sensory input from the primary sensorimotor area [16,17]. Therefore, the proprioceptive abilities of that area may be affected by disruptions to sensory maps [16,17]. It has been suggested that a disruption to the working body schema may result in motor and proprioceptive deficits [18]. The overlap in activation between these brain structures in both mental *manoeuvring* and performing an action [19,20], suggest that motor imagery and actions are mediated by the same brain circuit. Thus, factors that constrained actual, physical movement should also constrain imagined movements [21]. Integrity of the body schema can be investigated by implicit motor imagery, namely using behavioural tasks such as the left/right judgement task (LRJT) [16,22,23].

The LRJT evaluates the participants' ability to identify a picture of a body part (i.e. knee), shown in various orientations, as either being a picture of the left knee or the right knee. It requires making an initial decision regarding whether the image shown is a left or right knee and then affirming that decision by mentally orientating one's own knee or leg to match the posturing of the image shown [18,24]. An unimpaired working body schema is required for this task [25]. Therefore, reduced accuracy (ACC) is considered an indication of a disruption in the body schema (i.e. of their cortical proprioceptive representation) [16,24]. Conversely, reaction time (RT) reflects the total time required to assess which side that body part belongs to, rotating it to achieve a change of position mentally and making the final decision [25]. RT can also provide some insight to the brain's capacity to process incoming information (i.e. which may be reduced when pain is present) as well as the brain's ability to give priority or attentional bias towards a body part or an area of space [16,26].

Although Motor imagery performance (MIP) can be affected by multiple factors [16,18], no studies have investigated whether ACL deficiency may potentially cause alterations in implicit MIP. Given the impaired proprioceptive input in those with unilateral ACLD knees, it is possible that this disruption may be sufficient to cause impairments in the individual's cortical proprioceptive representation, as indicated by poor performance on the implicit motor imagery task. Thus, the first aim of this study was to determine whether LRJT performance differs between individuals with unilateral ACLD knee and those with a non-injured knee (i.e. healthy controls). We hypothesised that individuals with unilateral ACLD knee would be slower and less accurate than healthy controls in left/right judgements.

There is also evidence showing the existence of different patterns of brain activation during the dominant and non-dominant joints of lower limb [22,27]. In a cross-sectional study where 18 individuals who are right lower limb dominant were assessed for influence of limb dominance and joint specificity (proximal or distal) on the lateralisation of selected brain regions activity, it was found that the activation of basal ganglia was more lateralised during movement of the dominant lower limb joints compared to the non-dominant joints [28]. Based on the mean laterality index which facilitates the description of hemispheric dominance from functional activation patterns [29], they reported that the mean laterality index during the movement of joints of the dominant lower limb is approximately 3.5 times greater compared to the non-dominant ones in the basal ganglia. It has also been reported that LRJT performance is better when one makes a judgement on an image that corresponds to their dominant side [27,30,31]. Therefore, the second aim of our study was to determine whether the dominance of the ACLD leg (dominant versus non-dominant) influences MIP. We hypothesised that in a group of right dominant lower limb individuals, those with an injured ACL in their left knee (left ACLD knee group) would demonstrate greater motor imagery deficits than those with an injured ACL in their right knee (right ACLD injured group).

Previous work has also suggested that impairments in LRJT performance (i.e. implicit motor imagery ability) are often specific to the affected limb [26]. Specifically, individuals with unilateral complex regional pain syndrome of the upper limb ($n = 18$), have impaired LRJT performance on a hand laterality recognition task compared with healthy, matched control subjects, but that impairments occurred only when the hand image matched their affected limb [28]. In those with unilateral ACL deficiency, there are clearly differences between sides in afferent proprioceptive input to the brain [12,14]. However, it is unknown whether ACL rupture is sufficient to influence motor imagery of the affected limb. Thus, the third aim of our study was to determine whether impairments in LRJT performance are specific to knee image matching the side of ACL deficiency. We hypothesised that there will be greater motor imagery deficits when the image of the body part corresponds to the side of the ACL deficiency.

2. Methods

2.1. Participants

Two groups of participants – individuals with chronic, unilateral ACLD knee and healthy controls – were recruited. Potential participants with ACLD knee were identified from an orthopaedic clinic database. Those who met the inclusion criteria (e.g., had a unilateral ACLD knee diagnosed either by arthroscopy, magnetic resonance imaging (MRI) or clinically by trained

Table 1
Eligibility and participant recruitment source or method.

Study information	ACLD knee	Healthy control
Eligibility criteria	<ul style="list-style-type: none"> • Had a unilateral ACLD knee diagnosed either by arthroscopy, magnetic resonance imaging or clinically by trained clinicians and a healthy contralateral leg • Age between 16 and 50 years old • Duration of injury ≥ 6 months • Do not have: a history of fractures in the lower extremities; presence of knee OA (as determined by the American College of Rheumatology criteria: clinical examination only); surgery or intra-articular injection in the lower extremities in the past 6 months; history of meniscectomy of where more than 50% of the menisci had been removed; ACL injury to the contralateral knee; ligamentous injury to the contralateral limb in the past 6 months; history of meniscal repair or cartilage restoration procedure; and neurological pathologies or any other musculoskeletal pathology of the lower limbs (i.e. other ligament injuries or posterolateral corner injuries or patellofemoral pain syndrome) 	<ul style="list-style-type: none"> • Age between 16 and 50 years • Do not have: knee pain; previously diagnosed ligamentous injury at the knee joint by a healthcare physician or physiotherapist; previous surgery and an intra-articular injection in the lower extremities in the past 6 months
Source of participants	<ul style="list-style-type: none"> • Patient database of the North Sydney Orthopaedic and Sports Medicine Centre. Those who met the inclusion criteria were contacted via telephone or e-mail • Staff/students recruited from the University or volunteers from community via the University's research group's weekly online newsletter and word of mouth 	<ul style="list-style-type: none"> • Staff/students recruited from the University or volunteers from the community via the University research group's weekly online newsletter and word of mouth
Method of recruitment	Consecutive cases (based on date of injury)	Convenience sample

ACL, anterior cruciate ligament; ACLD, anterior cruciate ligament deficient; OA, osteoarthritis.

clinicians and a healthy contralateral leg) were either contacted by telephone or e-mail. Potential participants for the control group were recruited from the University or volunteers from the community via the University's research group's weekly online newsletter and word of mouth (see Table 1 for eligibility criteria specific to each group as well as the source of participants and methods of recruitment). The participants were recruited from November 2015 to July 2016. Written informed consent was obtained from all participants, and the evaluation was conducted during a single session by at the University's laboratory. All the participants were assessed by the same assessor. Informed consent was obtained from all participants. The study was approved by the University's ethical review board (2014/547).

2.2. Procedure

Participants completed a questionnaire that collected demographic information (age, height, weight, dominant leg) and other condition-specific information. For determining the dominant leg, participants were asked with which leg they would kick a ball [32]. Since the presence of pain and level of activity have been reported to influence LRJT performance [16,33], the following questionnaires/scales were also completed: visual analogue scale with 0 = no pain and 10 = worst pain imaginable, Knee Injury and Osteoarthritis Outcome Score (KOOS) (intraclass correlation coefficient (ICC) of >0.74 for each of its subsets) and Tegner Activity Scale (TAS) (ICC: 0.8) [34,35].

2.3. LRJT

The commercial program Recognise Online™ (<http://www.noigroup.com/recognise/>; noigroup.com, Adelaide, Australia) was used for the LRJT of the knee joint using a laptop. Participants were also shown two instructional images before each part of testing of knee. Twenty images of the knee were shown while participants were asked to determine whether the knee image was a left or right knee. Participants were instructed to make their judgments as quickly and accurately as possible. Images were displayed on screen for a maximum of five seconds or until the subject pressed a key indicating their choice. If no key was pressed, the image would automatically advance. Displayed images showed the knee in different planes, random angular orientation, position (e.g., flexed or extended) and sides. Some images featured the knee only while others included the foot (Figure 1). This is designated as the 'Vanilla' difficulty setting in Recognise Online™. Participants were seated comfortably with elbows at 90° with palms facing downwards. The left index finger was used on key A or the left arrow to indicate whether the picture was of a left knee and the right index finger was used on key D or the right arrow to indicate whether the picture was of a right knee. Participants were familiarised with the test and the computer set up by performing a practice trial with 20 images for which scores were not analysed. They then took a second trial of 20 images for which the data were analysed. The primary outcome measures included ACC (percentage of correct answers) and RT in seconds. The online programme Recognise was demonstrated to have good test–retest ICC values ranging from 0.80 to 0.92 (ACC) and 0.7 to 0.91 (RT) for within day trials [16,36].



Figure 1. Example of images displayed during left/right judgement task. Reproduced with permission from Noigroup Publications.

2.4. Statistical analysis

The statistical analysis was performed with a commercial software package (SPSS, version 21.0, SPSS Inc., Chicago, IL, USA). An independent sample *t*-test was used to determine whether there were differences in age and Tegner Score between the ACLD group and healthy controls. Based on visual inspection and the Shapiro–Wilk test, both ACC and the RT data in our study failed the normality assumption. As both log transformation and square root transformation failed to normalise the data, non-parametric statistics were used. We excluded four participants who were of left lower limb dominance (two in each group) for all analysis except for differences between all ACLD individuals and all healthy control individuals so as to create a more homogenous group.

A Kruskal–Wallis H-test was used to evaluate whether there were differences in the LRJT between groups. Specifically, between-group comparisons included: (1) participants with ACLD knee versus healthy controls; (2) participants with left ACLD knee versus controls; (3) participants with right ACLD knee versus healthy controls; (4) participants with left ACLD knee versus participants with right ACLD knee (all right lower limb dominant). Given that previous research in amputees (i.e. complete loss of proprioceptive input) suggests that LRJT performance is affected by the side of limb loss [31], we also considered left and right ACL deficiency separately and compared both left- and right-sided images. There are data to suggest LRJT performance may be affected by having an injury on the dominant limb compared to the non-dominant limb [27,30,31]. We, therefore, used the Kruskal–Wallis H-test to compare participants with left ACLD knee with those who had right ACLD knee participants.

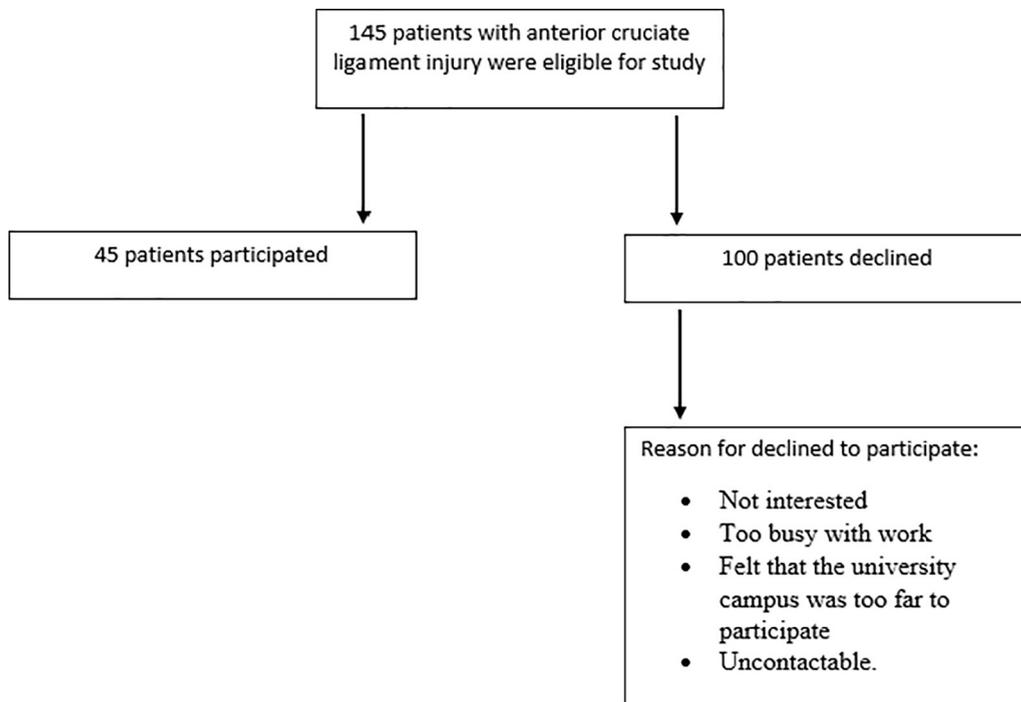


Figure 2. Participant recruitment chart.

Table 2
Participants' demographics.

Variables	ACL D, mean (SD)	Controls, mean (SD)
Number of participants	45	44
Age, years	37.2 (8.3)	34.6 (5.5)
Female, %	42.2	43.2
Duration of injury, months	58 (31.6)	
Leg dominance		
Right leg dominance, n	43	42
Right ACL D	17	
Left ACL D	26	
Left leg dominance, n	2	2
Right ACL D	2	
Left ACL D	0	
Height, m	1.7 (0.1)	1.7 (0.1)
Weight, kg	77.2 (14.5)	69.6 (15.7)
Body mass index, kg/m ²	26.4 (3.9)	24.3 (4.0)
KOOS		
Pain	93.1 (6.4)	
Symptoms	82.1 (21.0)	
Activity of daily living	98.6 (1.8)	
Sports & recreation	91.3 (10.2)	
Quality of life	64.1 (17.9)	
Overall	82.9 (12.0)	
VAS score during test (0–10)		
Affected leg VAS, n = 6	0.49 (1.3)	Nil
Unaffected leg VAS	Nil	Nil
Tegner Scale score before injury	6.6 (1.7)	
Tegner Scale score currently	4.9 (1.8)	4.4 (2.0)

Knee Injury and Osteoarthritis Outcome Score (KOOS) Grading: 100 indicates no symptoms and 0 indicates extreme symptoms. Tegner Scale score grading: possible score range 0–10; higher scores represent participation in higher-level activities. ACL D, anterior cruciate ligament deficient; SD, standard deviation; VAS, visual analogue scale.

Friedman's test was used for analysis that involved within-group comparisons. Friedman's test was used to determine whether there were differences in the LRJT specific to the side of ACL deficiency and between the healthy controls. The data are expressed as mean and standard deviation. *P*-values less than 0.05 were a priori defined as significant.

3. Results

One hundred and forty-five ($n = 145$) ACL-injured patients met our inclusion criteria during our search from the orthopaedic clinic's database. Forty-five (26 males and 19 females) of them agreed to participate in this study (see Figure 2 and Table 2). All patients had a complete ACL rupture, verified by MRI investigation. MRI investigation also demonstrated that among the individuals with ACL D knee, 31% had meniscal injuries, four percent had articular cartilage injuries, 22% had medial collateral ligament injuries, and two percent had lateral collateral ligament injuries. Forty-four healthy controls (25 males and 19 females) recruited through posters, online advertisements and word of mouth participated in the study (Table 2). Age ($P = 0.10$), and Tegner activity level scale score ($P = 0.16$) were not statistically different between the groups.

3.1. Between-group comparisons

3.1.1. ACC of left/right judgements

No statistically significant differences were identified in all of the comparisons; all ACL D and all healthy control individuals (left knee images: $P = 0.98$ and right knee images: $P = 0.62$) (Table 3, Figure 3), left ACL D and control (left knee images: $P = 0.39$ and right knee images: $P = 0.99$) (Table 3), right ACL D and control (left knee images: $P = 0.99$ and right knee images: $P = 0.38$) (Table 3) and individuals with left ACL D and right ACL D who are right lower limb dominant (left knee images: $P = 0.48$ and right knee images: $P = 0.35$) (Table 3, Figure 4).

3.1.2. RT of left/right judgement

Similarly, no statistically significant differences were identified in all of the comparisons; all ACL D and all healthy control (left knee images: $P = 0.53$ and right knee images: $P = 0.96$) (Table 3, Figure 3), individuals with left ACL D and control (left knee images: $P = 0.53$ and right knee images: $P = 0.96$) (Table 3), individuals with right ACL D and control (left knee images: $P = 0.50$ and right knee images: $P = 0.92$) (Table 3) and individuals with left ACL D and right ACL D who are right lower limb dominant (left knee images: $P = 0.99$ and right knee images: $P = 0.63$) (Table 3, Figure 4).

Table 3
Between-group analysis results.

Group	Outcome	Image	Median	IQR		χ^2	P
				Q1	Q3		
ACLD All (n = 45) vs Control (n = 44)	Accuracy	ACLD All – left image	78.8	70	90	0.001	0.98
		Control All – left image	79.1	70	90		
		ACLD All – right image	80.0	70	90		
		Control All – right image	77.9	70	90		
	Reaction Time	ACLD All – left image	2.1	1.8	2.5	0.402	0.53
		Control All – left image	2.1	1.7	2.6		
		ACLD All – right image	2.1	1.8	2.6		
		Control All – right image	2.3	1.7	2.6		
ACLD Left (n = 26) vs Control (n = 42)	Accuracy	ACLD Left – left image	76.9	70	90	0.727	0.39
		Control All – left image	80.0	70	90		
		ACLD Left – right image	78.5	70	90		
		Control All – right image	78.3	70	90		
	Reaction Time	ACLD Left – left image	2.1	1.8	2.5	0.404	0.53
		Control All – left image	2.0	1.7	2.5		
		ACLD Left – right image	2.2	1.7	2.7		
		Control All – right image	2.2	1.7	2.6		
ACLD Right (n = 17) vs Control (n = 42) ^a	Accuracy	ACLD Right – left image	79.0	70	90	0.000	0.99
		Control All – left image	80.0	70	90		
		ACLD Right – right image	83.8	70	90		
		Control All – right image	78.3	70	90		
	Reaction Time	ACLD Right – left image	2.1	1.9	2.4	0.449	0.50
		Control All – left image	2.0	1.7	2.5		
		ACLD Right – right image	2.1	1.9	2.8		
		Control All – right image	2.2	1.7	2.6		
ACLD Left (n = 26) vs ACLD Right (n = 17) ^a	Accuracy	ACLD Left – left image	76.9	70	90	0.498	0.48
		ACLD Right – left image	79.0	70	90		
		ACLD Left – right image	78.5	70	90		
		ACLD Right – right image	83.8	70	90		
	Reaction Time	ACLD Left – left image	2.1	1.8	2.5	0.000	0.99
		ACLD Right – left image	2.1	1.9	2.4		
		ACLD Left – right image	2.2	1.7	2.7		
		ACLD Right – right image	2.1	1.9	2.8		

IQR, interquartile range; Q1, 25th percentiles; Q3, 75th percentiles.

^a Left dominant lower limb participants excluded.

3.2. Within-group comparisons

3.2.1. ACC of left/right judgements

No statistically significant differences were identified in all of the comparisons; ACL injured knee and non-injured knee ($P = 0.49$) (Table 4, Figure 5), individuals with an injured ACL in their left knee and non-injured right knee ($P = 1.00$) (Table 4), individuals with an injured ACL in their right knee and non-injured left knee ($P = 0.32$) (Table 4). Additionally, there were no differences within the healthy control group who were right lower limb dominant when comparing left knee image (non-dominant) and right knee image (dominant) ($P = 0.62$) (Table 4).

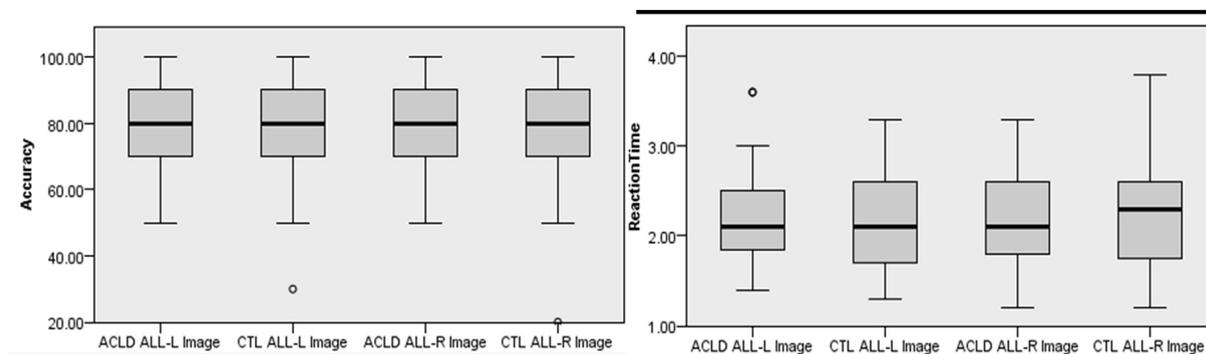


Figure 3. Distribution of accuracy and reaction time of left/right judgement values for anterior cruciate ligament deficient group and healthy controls. ACLD ALL-L Image, anterior cruciate ligament deficient – left knee image; ACLD All-R Image, anterior cruciate ligament deficient – right knee image; CTL All-L Image, control left knee image; CTL All-R Image, control right knee image.

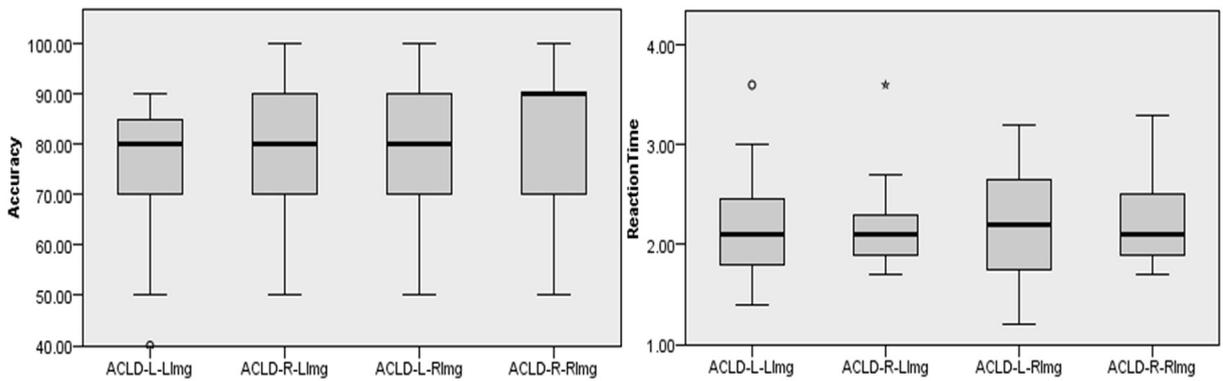


Figure 4. Distribution of accuracy and reaction time of left/right judgement values for individuals with left anterior cruciate ligament deficient knee and right anterior cruciate ligament deficient knee. ACLD-L-Limg, left anterior cruciate ligament deficient – left knee image; ACLD-L-Rimg, left anterior cruciate ligament deficient – right knee image; ACLD-R-Limg, right anterior cruciate ligament deficient – left knee image; ACLD-R-Rimg, right anterior cruciate ligament deficient – right knee image.

Table 4
Within-group analysis results.

Group	Outcome	Image	Median	IQR		Mean rank	P
				Q1	Q3		
ACL-injured knee vs. non-injured knee (n = 43) ^a	Accuracy	Injured	80.4	70	90	1.5	0.49
		Non-injured	79.6	70	90	1.5	
	Reaction time	Injured	2.1	1.8	2.5	1.5	0.52
		Non-injured	2.1	1.8	2.6	1.5	
ACL injured knee L vs. non-injured knee R (n = 26)	Accuracy	ACL-injured knee L	77.1	70	90	1.5	1.00
		Non-injured knee R	78.0	70	90	1.5	
	Reaction time	ACL-injured knee L	2.1	1.8	2.5	1.6	0.53
		Non-injured knee R	2.2	1.7	2.7	1.4	
ACL injured knee R vs. non-injured knee L (n = 17) ^a	Accuracy	ACL-injured knee R	82.7	70	90	1.6	0.32
		Non-injured knee L	80.8	70	90	1.4	
	Reaction time	ACL-injured knee L	2.1	1.9	2.6	1.5	1.00
		Non-injured knee L	2.1	1.9	2.6	1.5	
Control L knee vs. control R knee (n = 42) ^a	Accuracy	Control L knee	79.1	70	90	1.5	0.62
		Control R knee	77.9	70	90	1.5	
	Reaction time	Control L knee	2.1	1.7	2.6	1.5	0.64
		Control R knee	2.3	1.7	2.6	1.5	

IQR, interquartile range; Q1, 25th percentiles; Q3, 75th percentiles.

^a Left dominant lower limb participants excluded.

3.2.2. RT of left/right judgement

Similarly, no statistically significant differences were identified in all of the comparisons: ACL-injured knee and non-injured knee ($P = 0.52$) (Table 4, Figure 5), individuals with an injured ACL in their left knee and non-injured right knee ($P = 0.53$) (Table 4), individuals with an injured ACL in their right knee and non-injured left knee ($P = 1.00$) (Table 4). Additionally, there were no differences within the healthy control group who were right lower limb dominant when comparing left knee image and right knee image ($P = 0.64$) (Table 4).

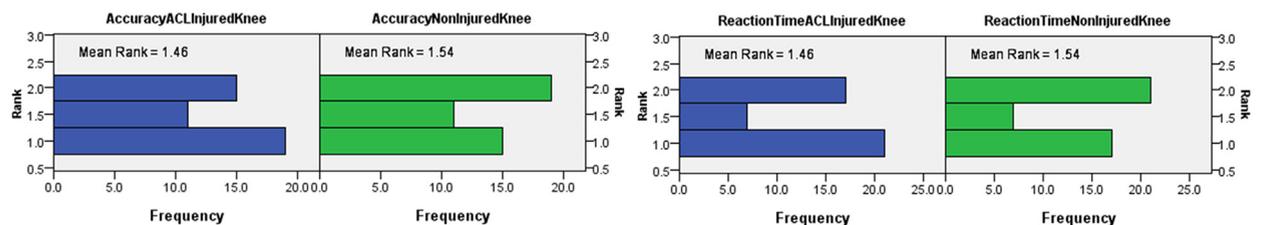


Figure 5. Distribution of accuracy and reaction time of left/right judgement values for anterior cruciate ligament (ACL) injured knee and non-injured knee. AccuracyACLinjuredKnee, accuracy in identifying images corresponding to ACL injured knee; AccuracyNoninjuredKnee, accuracy in identifying images corresponding to non-injured knee; ReactionTimeACLinjuredKnee, reaction time in identifying images corresponding to ACL injured knee; ReactionTimeNoninjuredKnee, reaction time in identifying images corresponding to non-injured knee.

4. Discussion

To our knowledge, this is the first study to investigate the integrity of the working body schema in individuals with chronic, unilateral ACL deficiency. Contrary to our hypotheses, our findings indicate that the working body schema, when measured using the LRJT, does not demonstrate deficits after a chronic disruption of the ACL in high-functioning individuals. This finding suggests that the loss of the mechanoreceptors of the ACL may not cause a disruption to the cortical proprioceptive representation maps (the working body schema) in high-functioning ACLD individuals.

The absence of ACC deficits in the LRJT in the participants evaluated in this study who had isolated ACLD knee indicated that the overall proprioceptive representation maps of the working body schema may be intact [24]. This suggests that the loss of proprioceptive information from the ruptured ACL may not play a major role in disrupting the integrity of the cortical proprioceptive representation of the body schema. Instead, the loss of proprioceptive information from the ruptured ACL may be compensated for by the information generated by the mechanoreceptors in different structures, such as capsules, tendons, muscles, and ligaments [37]. Good et al. [38], for example, did not observe any significant differences in joint position sense between the ACLD knee and their non-injured knee ($n = 18$). Additionally, Barrack et al. [39] who in their study, anaesthetised their participants' ($n = 10$) knee joint capsules and ligaments, leaving only the muscle spindles unaffected, did not identify any proprioceptive deficits, despite the absence of the information provided by the joint mechanoreceptors. Together these findings reflect the multifaceted characteristic of proprioceptive information, namely that it is not dependent on the receptors of the ACL alone. Conversely, these findings may either suggest that these proprioceptive tests may not be robust enough to detect whether there are disruptions of afferent input from the ACL or whether the afferent signals from the ACL are not necessary when performing these tests [40].

It is interesting to consider the role that the level of motor impairment may play in the proprioceptive acuity in the ACLD sample. The current sample of ACLD participants involved high-functioning individuals. Their activity levels, measured by the Tegner scale, were similar to that of the healthy control participants. They had an average score of 4.9 on the Tegner scale with 56% of them reporting that they had returned to their pre-injury activity level based on the Tegner scale. Additionally, they also reported high scores on the KOOS, especially the KOOS ADL (98.6 (1.8)) and KOOS sports and recreation (91.3 (10.2)) (Table 2). The ACLD participants also reported high scores on the KOOS activity of daily living and sports and recreation component scores (Table 2). The comparable level of activity between the control groups and the high functional status of our ACLD participants could also explain the absence of ACC deficits in the LRJT (i.e. indicating an intact cortical proprioceptive representation of the knee) [41]. This is in line with the studies which demonstrated that copers demonstrate different motor response strategies in comparison to non-copers which enable them to resume all preinjury activities, including sports, without episodes of knee giving way, thus not requiring surgery [41,42]. Considering that the ACLD participants in our study did not elect to have an ACL reconstruction and that they maintain a high level of activity suggests that they have developed strategies that allowed them to cope well with knee laxity. Thus, it is unclear whether the findings of the present study can be extrapolated to ACLD individuals who have lower functional status.

Previous work has shown deficits in LRJT performance (using images of lower limbs) in individuals with knee OA. Stanton et al. [18] demonstrated that individuals with knee OA have impaired ACC in the LRJT compared with healthy controls. Given that we excluded participants with clinical signs of knee OA, it meant that any changes in LRJT performance might be unique to ACLD and may not possibly be confounded by the presence of OA. Further, there is a growing body of evidence to suggest that the presence of pain influences LRJT performance [16,43]. Critically, the relative lack of pain in the present sample (only six of 45 ACLD participants reported low levels of pain while the rest reported no pain) also allows for specific evaluation of the influence of ACL deficiency alone on implicit motor imagery performance and strengthens our confidence that working body schema is intact in ACLD patients.

The absence of RT deficits in the LRJT in the participants evaluated in this study suggest that the capacity to process incoming information is intact in those with ACL deficiency and that there is no deficit in the brain's capacity to give priority or attention bias towards a body part or area of space [24,26]. Similar to ACC, RT is normally disrupted in participants who have pain [17,18,26]. However, RT deficits on the LRJT have also been shown in amputees without pain, suggesting that complete loss of incoming proprioceptive input has effects on cortical proprioceptive representation and processing of incoming information [44]. Thus, adding on to the suggestion that the absence of incoming proprioceptive input from a missing ACL may not be sufficient to disrupt these processes in high-functioning individuals. In summary, the lack of motor imagery deficits in the ACLD group may be due to the high level of function, absence of degenerative symptoms and low level of pain and, thus, should not be extrapolated to all ACLD patients, namely those with higher levels of disability.

While implicit motor imagery performance is not disrupted in high-functioning individuals with ACLD knee who do not have knee pain, it is possible that the participants did not solely use implicit motor imagery but instead may have also used an alternative strategy such as visual object recognition [45]. Visual object recognition involves using features of the image to determine laterality (e.g., toe of the foot), such that implicit motor imagery (i.e. mentally manoeuvring one's own limb to match the posturing of the pictured image) is not used [45]. However, the likelihood of participants using visual object recognition is low given that the images used in the present study included knees being displayed in different planes, random angular orientation and position (e.g., flexed or extended), displaying the knee only or with adjacent joints, thus making the task quite complex. Previous research has demonstrated that motor imagery strategy is used when tasks are complex and visual object recognition with tasks that are simpler [46]. Future studies, therefore, should have clear strategies to establish that motor imagery has been used to complete the task. This can be performed, for example, by comparing RTs to images at

different orientations (e.g., images at 180° take longer to identify than those at 0°) and by determining that the participants, at a group level, show evidence of the biomechanical constraints of movement during the LRJT task (e.g., images that show an awkward posture take much longer to respond to) which are known to be present when implicit motor imagery is being used [46].

5. Limitations

As we did not investigate whether cortical changes were present in our group of individuals with chronic ACLD knee, we are unable to determine whether the cortical changes that were observed in previous studies of ACLD participants were present in our sample. Therefore, future studies may consider investigating within the same group of individuals with chronic unilateral ACLD knee, for the presence of cortical changes and LRJT performance. Additionally, our study selection criteria may have led to a natural selection of high-functioning ACLD knee participants. Therefore, the results of this study cannot be extrapolated to ACLD individuals with higher levels of disability. The gathered data was not normally distributed. All the participants demonstrated good ACC and fast RT. This in turn may cause a ceiling effect which can make differentiation of participants' performance difficult. Therefore, caution should be exercised when interpreting the results of the data being presented. A priori sample size calculation was not performed for this study; however, the small effect sizes make it unlikely that the lack of group differences found here was due to low power. The present study also recruited participants over a broad age range and over a wide range of injury durations. While increasing generalisability of results, it may be that subgroups of participants may exist. The present study was not powered to formally investigate presence of such subgroups, but it would be relevant to consider both younger vs older participants as well as short versus long injury duration. The present study did not assess proprioceptive acuity in participants. Thus, further work is needed to ascertain whether or not proprioceptive impairment following an ACL injury may result in differing LRJT performance results. It has been reported that the LRJT is a complicated mental task that includes cognitive, sensory, motor and behavioural processes [47]. Differences between individuals with and without pain and improvement in LRJT performance may be attributed to any of these factors. Therefore, LRJT may not be as valuable when used as a stand-alone evaluation of mental imagery. It could be used with sensory testing [47].

6. Conclusion

Motor imagery performance is not disrupted in individuals with chronic ACLD knees who have high levels of function, no degenerative symptoms and low levels of pain. In this select ACLD group, the disruption of afferent signals due to the loss of the ACL may be compensated for by other mechanisms. Therefore, the loss of the mechanoreceptors of the ACL may not play a major role in the integrity of the working body schema.

Conflict of interest

The authors have declared no conflicts of interest. T.R.S. received travel and accommodation support from Eli Lilly Ltd.; this was unrelated to the present topic.

References

- [1] Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med* 2013;41:216–24.
- [2] Janssen KW, Orchard JW, Driscoll TR, van Mechelen W. High incidence and costs for anterior cruciate ligament reconstructions performed in Australia from 2003 to 2004 to 2007–2008: time for an anterior cruciate ligament register by Scandinavian model? *Scand J Med Sci Sports* 2012;22:495–501.
- [3] Leporace G, Metsavaht L, Oliveira LPd, Nadal J, Batista LA. Motor coordination during gait after anterior cruciate ligament injury: a systematic review of the literature. *Rev Bras Ortop* 2013;48:293–9.
- [4] Barrack RL, Skinner HB, Buckley SL. Proprioception in the anterior cruciate deficient knee. *Am J Sports Med* 1989;17:1–6.
- [5] Corrigan JP, Cashman WF, Brady MP. Proprioception in the cruciate deficient knee. *J Bone Joint Surg Br* 1992;74:247–50.
- [6] Johansson H, Sjolander P, Sojka P. A sensory role for the cruciate ligaments. *Clin Orthop Relat Res* 1991;161–78.
- [7] Schutte MJ, Dabezies EJ, Zimny ML, Happel LT. Neural anatomy of the human anterior cruciate ligament. *J Bone Joint Surg Am* 1987;69:243–7.
- [8] Zimny ML, Schutte M, Dabezies E. Mechanoreceptors in the human anterior cruciate ligament. *Anat Rec* 1986;214:204–9.
- [9] Proske U, Gandevia SC. The proprioceptive senses: their roles in signalling body shape, body position and movement, and muscle force. *Physiol Rev* 2012;92:1651–97.
- [10] Lephart SM, Pincivero DM, Giraldo JL, Fu FH. The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med* 1997;25:130–7.
- [11] Park HB, Koh M, Cho SH, Hutchinson B, Lee B. Mapping the rat somatosensory pathway from the anterior cruciate ligament nerve endings to the cerebrum. *J Orthop Res* 2005;23:1419–24.
- [12] Kapreli E, Athanasopoulos S, Gliatis J, Papatathanasiou M, Peeters R, Strimpakos N, et al. Anterior cruciate ligament deficiency causes brain plasticity: a functional MRI study. *Am J Sports Med* 2009;37:2419–26.
- [13] Grooms DR, Page SJ, Nichols-Larsen DS, Chaudhari AM, White SE, Onate JA. Neuroplasticity associated with anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther* 2017;47:180–9.
- [14] Valeriani M, Restuccia D, Di Lazzaro V, Franceschi F, Fabbriani C, Tonali P. Central nervous system modifications in patients with lesion of the anterior cruciate ligament of the knee. *Brain* 1996;119:1751–62.
- [15] Fleming GW. Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. (*Brain*, vol. lx, p. 389, Dec., 1937). *Br J Psychiatry* 1938;84:868.
- [16] Bray H, Moseley GL. Disrupted working body schema of the trunk in people with back pain. *Br J Sports Med* 2011;45:168–73.
- [17] Luomajoki H, Moseley GL. Tactile acuity and lumbopelvic motor control in patients with back pain and healthy controls. *Br J Sports Med* 2011;45:437–40.

- [18] Stanton TR, Lin CW, Smeets RJ, Taylor D, Law R, Lorimer Moseley G. Spatially defined disruption of motor imagery performance in people with osteoarthritis. *Rheumatology (Oxford)* 2012;51:1455–64.
- [19] Grezes J, Decety J. Functional anatomy of execution, mental simulation, observation, and verb generation of actions: a meta-analysis. *Hum Brain Mapp* 2001;12:1–19.
- [20] Ganis G, Keenan JP, Kosslyn SM, Pascual-Leone A. Transcranial magnetic stimulation of primary motor cortex affects mental rotation. *Cereb Cortex* 2000;10:175–80.
- [21] Dahm SF, Rieger M. Cognitive constraints on motor imagery. *Psychol Res* 2016;80:235–47.
- [22] Jeannerod M. Neural simulation of action: a unifying mechanism for motor cognition. *NeuroImage* 2001;14:S103–9.
- [23] Schwoebel J, Friedman R, Duda N, Coslett HB. Pain and the body schema: evidence for peripheral effects on mental representations of movement. *Brain* 2001;124:2098–104.
- [24] Parsons LM, Fox PT. The neural basis of implicit movements used in recognising hand shape. *Cogn Neuropsychol* 1998;15:583–615.
- [25] Parsons LM. Integrating cognitive psychology, neurology and neuroimaging. *Acta Psychol (Amst)* 2001;107:155–81.
- [26] Moseley GL. Why do people with complex regional pain syndrome take longer to recognise their affected hand? *Neurology* 2004;62:2182–6.
- [27] Ionta S, Blanke O. Differential influence of hands posture on mental rotation of hands and feet in left and right handers. *Exp Brain Res* 2009;195:207–17.
- [28] Kapreli E, Athanasopoulos S, Papanthasiou M, Van Hecke P, Strimpakos N, Gouliamos A, et al. Lateralization of brain activity during lower limb joints movement. An fMRI study. *NeuroImage* 2006;32:1709–21.
- [29] Seghier ML. Laterality index in functional MRI: methodological issues. *J Magn Reson Imaging* 2008;26:594–601.
- [30] Ní Choisdealbha Á, Brady N, Maguinness C. Differing roles for the dominant and non-dominant hands in the hand laterality task. *Exp Brain Res* 2011;211:73–85.
- [31] Nico D, Daprati E, Rigal F, Parsons L, Sirigu A. Left and right hand recognition in upper limb amputees. *Brain* 2004;127:120–32.
- [32] van Melick N, Meddeler BM, Hoogeboom TJ, Nijhuis-van der Sanden MWG, van Cingel REH. How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults. *PLoS One* 2017;12:e0189876.
- [33] Botnmark I, Tumilty S, Mani R. Tactile acuity, body schema integrity and physical performance of the shoulder: a cross-sectional study. *Man Ther* 2016;23:9–16.
- [34] Briggs KK, Lysholm J, Tegner Y, Rodkey WG, Kocher MS, Steadman JR. The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. *Am J Sports Med* 2009;37:890–7.
- [35] Salavati M, Akhbari B, Mohammadi F, Mazaheri M, Khorrami M. Knee injury and Osteoarthritis Outcome Score (KOOS); reliability and validity in competitive athletes after anterior cruciate ligament reconstruction. *Osteoarthr Cartil* 2011;19:406–10.
- [36] Dey A, Barnsley N, Mohan R, McCormick M, McAuley JH, Moseley GL. Are children who play a sport or a musical instrument better at motor imagery than children who do not? *Br J Sports Med* 2012;46:923–6.
- [37] Johansson H, Sjolander P, Sojka P. Receptors in the knee joint ligaments and their role in the biomechanics of the joint. *Crit Rev Biomed Eng* 1991;18:341–68.
- [38] Good L, Roos H, Gottlieb DJ, Renstrom PA, Beynon BD. Joint position sense is not changed after acute disruption of the anterior cruciate ligament. *Acta Orthop Scand* 1999;70:194–8.
- [39] Barrack RL, Skinner HB, Brunet ME, Haddad Jr RJ. Functional performance of the knee after intraarticular anaesthesia. *Am J Sports Med* 1983;11:258–61.
- [40] Relph N, Herrington L, Tyson S. The effects of ACL injury on knee proprioception: a meta-analysis. *Physiotherapy* 2014;100:187–95.
- [41] Fonseca ST, Ocarino JM, Silva PL, Guimaraes RB, Oliveira MC, Lage CA. Proprioception in individuals with ACL-deficient knee and good muscular and functional performance. *Res Sports Med* 2005;13:47–61.
- [42] Houck JR, De Haven KE, Maloney M. Influence of anticipation on movement patterns in subjects with ACL deficiency classified as noncopers. *J Orthop Sports Phys Ther* 2007;37:56–64.
- [43] Stanton TR, Leake HB, Chalmers KJ, Moseley GL. Evidence of impaired proprioception in chronic, idiopathic neck pain: systematic review and meta-analysis. *Physical therapy* 2016;96(6):876–87.
- [44] Moseley GL, Brhyn L, Ilowiecki M, Solstad K, Hodges PW. The threat of predictable and unpredictable pain: differential effects on central nervous system processing? *Aust J Physiother* 2003;49:263–7.
- [45] Logothetis NK, Sheinberg DL. Visual object recognition. *Annu Rev Neurosci* 1996;19:577–621.
- [46] ter Horst AC, van Lier R, Steenbergen B. Mental rotation task of hands: differential influence number of rotational axes. *Exp Brain Res* 2010;203:347–54.
- [47] Pelletier R, Bourbonnais D, Higgins J, Mireault M, Danino MA, Harris PG. Left right judgement task and sensory, motor, and cognitive assessment in participants with wrist/hand pain. *Rehabil Res Pract* 2018;2018:1530245.