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Motor control after anterior cruciate ligament reconstruction

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Chapter 5

Movement Patterns of Patients Immersed in Virtual Reality after ACL Reconstruction

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ABSTRACT

Purpose: Despite ACL-reconstruction (ACLR), patients often show persistent asymmetric movements patterns during activities of daily living and sport specific tasks. It is conceivable that patients use an attentional focus that is directed to conscious control of the movements (internal focus) to avoid loading their involved leg. Virtual reality is a powerful tool for simulating aspects of the real world. The purpose of this study is to evaluate the influence of immersion in virtual reality environment on knee biomechanics in patients after ACLR. The patients were be embedded in a virtual reality setting in order to distract them from their conscious control of the knee. It is hypothesized that patients reach a more normalized movement pattern in a virtual reality environment compared to a non-virtual reality environment because it distracts them from their conscious motor control.

Methods: Twenty athletes following ACLR and 20 healthy controls (CTRL) performed a step down task in both a non-virtual reality environment and in a virtual reality environment. Knee joint biomechanics were measured and analyzed during each single-leg landing.

Results: A significant main effect was found for environment for knee flexion excursion ($P = 0.031$). Significant interactions differences were found between environment and groups for vertical ground reaction force (GRF) ($P = 0.004$), knee moment ($P < 0.001$), knee angle at peak GRF ($P = 0.011$) and knee flexion excursion ($P = 0.032$). In virtual reality environment knee biomechanics of patients after ACLR increased more than those of controls.

Conclusion: Patients after ACLR immersed in virtual reality environment demonstrated knee joint biomechanics that approximate those of CTRL. The results of this study suggest that virtual reality environment distracts patients after ACLR from conscious motor control. The results of this study suggest that altered movement patterns after ACLR may be effectively targeted with novel motor learning techniques.

Key words: Anterior cruciate ligament; motor learning; external focus; knee biomechanics

Level of evidence: Diagnostic study, III

INTRODUCTION

Between 250,000 – 300,000 anterior cruciate ligament (ACL) injuries occur in the United States per year[1], and most athletes are advised to undergo ACL-reconstruction (ACLR) with the expectation that surgery will restore knee function and facilitate return to previous levels of activity.[2] However, successful ACLR in terms of restoring the mechanical stability of the knee joint is not synonymous with restoration of normal knee function.[3] After ACLR, altered movement patterns and neuromuscular impairments are consistently found during activities such as walking, running and jumping.[4-12]
Asymmetries in multidimensional knee biomechanics (kinematics and kinetics) during daily tasks as well as athletic activities are reported for up to five years after ACLR.[4,13-19]
Altered movement patterns after ACLR may be useful in the acute stage after surgery as the patient may choose to move the involved leg carefully to reduce pain or prevent instability. Theoretically, altered movement patterns should be time dependent if we accept the premise that movement has potential to be restored to normal levels during the course of rehabilitation after ACLR. Unfortunately, it was recently demonstrated that biomechanical deficits evidenced by reduced force generation and force absorption are independent of time after ACLR.[20]
There is a need to expand the current body of knowledge in understanding how and why altered movement patterns develop and can be reversed with rehabilitation following ACLR. Concepts of motor learning may help shrink this gap in knowledge. Motor learning is defined as the process of the person’s capability in acquiring motor skills with a permanent change.[21,22]
Effective motor control calls for an efficient information processing between the body, brain and environment (embodied cognition).[23] The classical view is that cognitive control is necessary as a prerequisite before a subject reaches the stage during which movement control occurs more or less automatically.[24] Based on this contention, during the early stages of motor re-learning, the execution of movement requires attention, so that there exists a dependency on cognitive control.[24]
Based on aforementioned, it may be plausible that patients after ACLR may utilize an increased attentional, cognitive focus on movement which inhibits the learning process of regaining normal movements. Researchers have defined an internal and external focus to describe attentional demands in motor learning and rehabilitation to (re-) acquire motor skills.[25-30] Typically, feedback provided by clinicians during rehabilitation sessions refers to attention of body movements. The treating clinician may tell a patient who has an altered gait pattern after ACLR to extend the knee more during the stance phase. In the motor learning domain, this type of attentional focus is termed “internal focus”.[31] Conversely, an external focus of attention is induced when a patient’s attention is directed towards the outcome or effects of the movement (e.g., “imagine to kick a ball”, to facilitate extension of the knee).

Adopting an external focus has been shown to be more effective in motor learning because it directs the patient's attention away from their own movements and shifts it towards the outcome of movements.[21] A continued internal focus may be detrimental to motor learning as conscious control of movements interferes with automatic motor control processes that would "normally" regulate the movement.[32] Patients who actively intervene in the control of their movements, i.e. using an internal focus, seem to constrain the motor system and degrade the natural movement. Such action results in decreased performance and altered movement patterns.[30] Clinically, it appears that patients after ACLR utilize such an internal focus to constrain the movements of the knee joint although this strategy has not been previously evaluated or reported in the literature to the best of our knowledge. Therefore, the challenge is to develop experiments that might test these hypotheses. Virtual reality may be an appropriate tool because it allows for manipulation of visual and auditory feedback to reassure that all subjects are examined under the identical circumstances. In addition, with virtual reality it is possible to manipulate the environment that would be impractical or impossible to create in the real world.[33] Kinematics of movements performed in a virtual reality environment are remarkably similar to those when acting in the real world.[33]
Virtual reality may also be employed in patients after ACLR to measure the changes in strategy they use as a result of a change in environmental embedding. This embedding may "distract" the patient after ACLR resulting in a change of the motor control due to a change in attention.[34] The purpose of the current study was to evaluate the influence of immersion in virtual reality on movement patterns in patients after ACLR while performing a step down task. We hypothesized that virtual reality techniques aimed to alter attentional focus will increase knee flexion angle, knee moment and vertical ground reaction force in patients following ACLR.

MATERIAL AND METHODS

Subjects

We recruited 20 patients after ACLR (10 males, 10 females) with a mean age of 23.5 ± 4.3 years from the Orthopaedic Surgery department of the Martini Hosptial, Groningen, the Netherlands. The patients after ACLR were all cleared to return to sports by their physical therapist and the orthopedic surgeon. Inclusion criteria for ACLR group were: 1) between the ages of 18-45, 2) < one year between injury and ACLR, 3) patient participated in rehabilitation program outlined by the hospital and 4) active in sports after surgery. Exclusion criteria were 1) swelling of the operated knee joint, 2) varus malalignment of the knee, 3) grade 3 injury of the collateral ligaments, 4) concomitant ligamentous injuries to the posterolateral corner, 5) > 50% base menisectomy, 6) traumatic cartilage injuries, 7) degenerative changes of the knee joint, 8) surgical procedures or injuries to the contralateral leg and 9) neurological and/or vestibular disease. Patients after ACLR were tested at a mean of 8.9 ± 2.3 months after surgery. The CTRL group included 20 healthy subjects (10 males and 10 females) with a mean age of 22.7 ± 2.3 years. The exclusion criteria for the CTRL group were as follows: 1) surgical procedures or injuries to the contralateral leg and 2) neurological and/or vestibular disease. The characteristics of all subjects are shown in Table 1.

Table 1. Demographic data of control and ACLR subjects, mean (± SD).

	Control subjects	ACLR subjects
Age (years)	22.7 ± 2.3	23.5 ± 4.3
Gender (n)	male (10), female (10)	male (10), female (10)
Mass (kg)	71.4 ± 10.7	75.2 ± 12.3
Height (cm)	178.9 ± 10.0	179.2 ± 8.4
Left leg length (cm)	93.5 ± 6.9	94.0 ± 5.9
Right leg length (cm)	93.4 ± 6.9	94.0 ± 5.9
Dominant leg[a] (n)	left (3), right (17)	left (0), right (20)
Injured knee (n)	-	left (9), right (11)
Time since injury (months)	-	18.1 ± 12.3
Time since surgery (months)	-	8.9 ± 2.3
Hours sport per week (prior injury for ACLR subjects)	4.7 ± 2.6	6.8 ± 3.8
IKDC score*	97.6 ± 5.1	77.9 ± 12.9

[a] Dominant leg was defined as the leg with which subject would kick a ball. * Significant difference between groups ($p<0.001$).

We designed our study based on continuous response variables from independent control and experimental subjects with one control(s) per experimental subject. Based on a similar study related to biomechanics during stair descent[15] a minimum of nine study subjects per group was needed to reject the null hypothesis with 80% power and a Type I error probability at 0.05.

Test protocol

Instrumentation

All subjects wore their own athletic shoes during the test session. Prior to testing, each subject was fitted with 11 retroreflective markers of 14 mm in diameter (MotionCap, USA). The markers were placed on top of the head, spinous process Th7, midline PSIS and bilateral on greater trochanter, lateral epicondyle femur, lateral malleolus and base 5th metatarsal. Before each data collection session, the motion analysis system was calibrated to manufacturer recommendations. Each subject underwent motion analysis during a step down from a 20 cm high box onto two force plates (Bertec Corporation, Columbus, USA) of 40×60 cm that were embedded in the floor in front of the box. Twelve infrared cameras V8 Workstation 4.6 (VICON, Oxford, UK) were positioned in the Computer Assisted Rehabilitation Environment - CAREN lab (Motek Medical, Amsterdam, the Netherlands) that defined a capture volume (m^3) with dimensions of 4.5 × 4 × 2.5 m. In addition, sorting of template based marker matching was obtained prior to each trial. The 3D marker positions recorded during the trials were captured by the Vicon motion analysis system (VICON, Oxford, UK). These data were transferred to DFlow (Motek Medical, Amsterdam, the Netherlands) at a sample rate of 120 Hz via a TCP-IP network.

Data collection

The sequence of stepping down for patients was eight trials with the involved leg followed by eight trials for the uninvolved leg. CTRL first stepped down with the dominant leg, defined as the leg which they would kick a ball with, followed by the non-dominant leg. Other than instructions on when to step, the subjects were told to keep the arms across the chest to prevent occlusion of the hip markers. The step was deemed correct by the experimenter when the subject landed with one foot on the force plate. The experiment was divided in a non-virtual reality and a virtual reality environment condition which was custom developed for the purpose of this study. The non-virtual environment depicted a traffic light which changed from red to green projected on a grey 3.65×2.70 m screen. In comparison, the virtual reality environment was a traffic environment depicting a city street, with high buildings and a crosswalk with a pedestrian traffic light and cars projected on the screen passing from left to the right (Figure 1).

We controlled for visual influences as patients were asked in both conditions to look at the same screen. In addition to visual input, stereo sound with common traffic noise was added to the virtual reality environment. In both environments, the traffic light was placed at the exact same spot and changed randomly from red to green between 15 – 25 seconds. The subjects were instructed to step down once the red light changed to green. For the virtual environment, all subjects received the instruction to pay attention to the oncoming traffic. All subjects stepped down first in non-virtual reality followed by the virtual reality environment. All subjects performed a total of 32 trials (eight trials for each leg per environment).

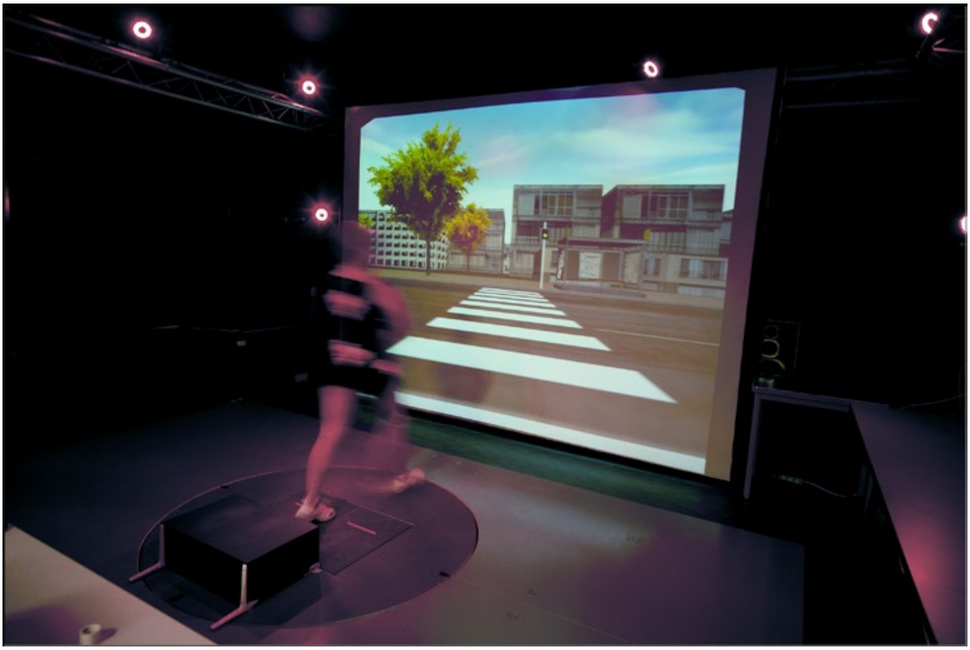

Figure 1. Subject in the virtual reality environment depicting a traffic scene with a crosswalk and a pedestrian traffic light. Upon switching the traffic light from red to green, the subject stepped down the box onto the force plate placed in front of the box.

Data processing

Data processing was performed with D-Flow (Motek, the Netherlands) and MATLAB version R2010a (The MathWorks, Inc., Natick, Massachusetts, USA). The raw data was processed with a zero lag filter with smooth cut-off in the frequency domain to avoid ringing with minimal jerk convolution filter of a bell shaped profile with the signal. A custom program was written to calculate the various biomechanical variables. The peak vertical ground reaction force (GRF) was calculated as the peak magnitude of the landing force normalized to body weight (N/BW). The peak internal knee extension moment was normalized to BW (Nm/BW). The knee angle was defined as the angle at peak GRF. Knee flexion excursion was the displacement of the knee (in degrees) in the sagittal plane and was calculated from the knee angle during initial foot contact (IC) to the largest flexion angle during stance phase. IC was defined when the vertical GRF exceeded 10N.

Statistical analysis

A generalized linear mixed model analysis in SPSS version 20 (SPSS, Inc., Chicago, USA) was applied to examine the influence of environment (virtual reality versus non-virtual reality) in the two subject groups. Data was analyzed with an ANOVA in the context of a linear mixed model because we did not have eight repeated measures for each individual. The involved leg of individuals in the ACLR group was compared to the non-dominant leg of individuals in the CTRL group which has been shown to accurately detect differences between groups.[35] The dependent variables of interest were peak vertical GRF, maximum internal knee extension moment, knee angle at peak GRF and knee flexion excursion. Main effects of group (ACLR/CTRL) and environment, and their interaction were included in the model. Based on the Likelihood Ratio test, the interaction term was removed from the model if the P-value was larger than 0.05. The intercept was assigned to the non-dominant leg of the CTRL group. Statistical significance was established a priori at $P < 0.05$.

RESULTS

Significant interactions between environment and groups were found for the dependent variables GRF ($P = 0.004$), peak internal knee extension moment ($P < 0.001$), knee angle at peak GRF ($P = 0.011$) and knee flexion excursion ($P = 0.032$) (Table 2). This was demonstrated by significant differences for all measurements. The GRF was lower in the ACLR group in non-virtual reality (1.41 N/BW ± 0.32) compared to CTRL (1.52 N/BW ± 0.19) but increased when immersed in virtual reality (1.52 N/BW ± 0.35) with no change in the CTRL group. An increase in peak internal knee moment in virtual reality was also noted for the ACLR group (1.05 Nm/BW ± 0.48 to 1.20 Nm/BW ± 0.53). Interestingly, the CTRL showed a decrease (1.24 Nm/BW ± 0.60, 1.19 Nm/BW ± 0.56) in knee moment in virtual reality compared to non-virtual reality. Peak knee angle during non-virtual in the ACLR group (27.00° ± 8.72) increased marginally in virtual reality (28.13° ± 7.64) and decreased in the CTRL group (26.51° ± 7.62, 25.71° ± 7.38). The influence of virtual reality on knee flexion excursion was significantly different between groups, with the ACLR group demonstrating a very small increase (12.64° ± 4.82, 12.83° ± 4.05) compared with a decrease for CTRL (14.14° ± 5.94, 13.01° ± 4.86).

Table 2. Results for the dependent biomechanical variables during non-virtual reality and virtual reality for the ACLR and CTRL group.

	NVR	**VR**	**NVR**	**VR**	***P* value**	***P* value**	***P* value***
	ACLR (mean ± SD)	ACLR (mean ± SD)	CTRL (mean ± SD)	CTRL (mean ± SD)	ACLR versus CTRL	Environment	Interaction Group x Environment
Peak vertical GRF (N/BW)	1.41 ± 0.32	1.52 ± 0.35	1.52 ± 0.19	1.52 ± 0.17	0,816	0,737	0.004*
Peak internal knee extension moment (Nm/BW)	1.05 ± 0.48	1.20 ± 0.53	1.24 ± 0.60	1.19 ± 0.56	0,847	0,388	<0.001*
Knee angle at peak GRF (degrees)	27.00 ± 8.72	28.13 ± 7.64	26.51 ± 7.62	25.71 ± 7.38	0,268	0,466	0.011*
Knee flexion excursion (degrees)	12.64 ± 4.82	12.83 ± 4.05	14.14 ± 5.94	13.01 ± 4.86	0,875	0.031*	0.032*

Abbreviations: NVR, non-virtual reality; VR, virtual reality; ACLR, involved leg ACL group; CTRL, non-dominant leg of the CTRL group; GRF, ground reaction force; BW, body weight; SD, standard deviation; * denotes statistical significance P < 0.05

DISCUSSION

The purpose of the current study was to evaluate the influence of altered attention focus by immersion in a virtual reality environment on step down performance in patients after ACLR. We employed a step down task to quantify differences in dynamics of the knee joint when different focus of attention was provided to the patients.

A significant interaction was found between groups and environments for all outcome variables; GRF and peak internal extension knee moment. Interestingly, peak GRF values for the ACLR group when in virtual reality, approached those of healthy subjects. The influence of virtual reality was more pronounced in ACLR than in the CTRL group.

The task had to be identical from a biomechanical perspective for both groups during both conditions. That was the primary reason why virtual reality was used to help control for attentional demands. It is difficult to meet these criteria for the practice of locomotor tasks in currently constrained indoor and outdoor settings. Virtual reality typically refers to the use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear and feel similar to real world objects and events. Virtual reality enables researchers to analyze task performance in valid situations similar to real life, yet under experimentally controlled conditions.[33]

The influence of virtual reality was more pronounced in ACLR than in the CTRL group. We tested patients after ACLR in a not meaningful laboratory environment and a meaningful environment showing a real life scene to measure the changes in movement patterns. Although we have only studied the influence of the manipulated virtual environment on biomechanics of the knee, we suggest that this may have influenced the focus of attention. It needs to be recognized that attentional focus was not directly monitored to determine whether they were internally or externally focused. However we employed the virtual environment to invite subjects to a more external focus and from the results do we do assume that this may indeed be related to the focus of attention as this was the only manipulated variable. A recent study suggested that virtual reality promotes a dissociative attentional focus, acting as a “distractor” from the exercise performed.[36]

A continued internal focus may be detrimental to motor learning and even more detrimental to motor control restoration in patients following ACLR. When patients adopt an internal focus of attention, they are consciously focusing on the movement characteristics of their body.[37] Research indicates that an external focus of attention enhances performance and motor learning.[21] Instructions and feedback for motor skill learning during rehabilitation indicate that 95% of physical therapists provide feedback instructions with such an internal focus.[38] A typical example is a clinician instructing a patient to straighten the knee more during the stance phase in gait. However, providing instructions that induce an external focus of attention have been shown to result in superior skill acquisition over using instructions that induce such internal foci of attention.[39-42] For example, larger improvements in gait are achieved if gait training is coupled with virtual reality as compared to standard gait training.[43,44]

The benefits of an external focus have also been presented in patients suffering from an ankle sprain. The group practicing the acquisition of a postural skill task using an external focus significantly improved the ability to maintain balance, whereas those using an internal focus attention training program did not achieve significant improvement in balance measures.[45]

Several studies have shown that biomechanics (kinematics and kinetics) are not restored to normal levels after the surgical procedure.[14,46,47] Recently, it was established that unilateral force development (vertical jump height) and absorption (normalized VGRF) persist in an athlete’s single-limb performance after ACLR that were not related to elapsed time after the surgery, although athletes after ACLR had returned to sports.[20] Hence, after conclusion of the rehabilitation and clearance for return to sports, biomechanical deficits are still present indicating that current ACLR rehabilitation may not be optimally effective in addressing deficits related to the surgical intervention.[48] Although there are good intuitive reasons to suggest a more novice-like mode of motor learning by inducing an internal focus in an attempt to target these asymmetries, this strategy may not be optimal.[49] An internal focus results in an increase of co-contraction of agonists and antagonists, which in turn may cause “freezing” by limiting the degrees of freedom of movements, and in the recruitment of unnecessary motor units within muscles, which adds “noise” to the motor system.[50]

The clinical relevance of this study is that we were able to demonstrate that movement patterns can be modified in patients after ACLR using virtual reality. Perhaps virtual reality causes a decrease of the internal focus. In other words, less internal focus allows for more efficient movement performance.[51] The current study may aid in our understanding how we can target leg asymmetries after ACLR. The incidence of a second injury to the ACLR knee or injury to the contralateral knee may exceed 20% in young athletes who returned to competitive activities.[19] The most common biomechanical factor with increased risk of second injury is asymmetrical loading during sports related tasks.[19,47]

Cumulatively, the incorporation of external focus instructions into rehabilitation practice can potentially enhance the effectiveness and efficiency of rehabilitation. Current data shows that this can be realized by integrating easily available technology into rehabilitation programs to enhance motor learning capabilities with the ultimate goal to reduce risk of second injury risk. We acknowledge that virtual reality is not readily available to clinicians. In a recent RCT that compared a Nintendo Wii Fit (Nintendo, Kyoto, Japan) balance board program with conventional rehabilitation after ACLR, similar results were obtained in improving muscle strength, balance, and coordination and response time tasks.[52] This type of technology can easily be integrated in daily practice.

Several limitations of this study need to be acknowledged. No baseline data of ACLR subjects prior to surgery were available. A pre- and post-operative design may useful to directly assess the changes after ACLR. We have only studied the influence of the manipulated environment and only suggest that this may have influenced the focus of attention. It would have been beneficial to include questionnaires to gain a level of understanding regarding what participants focused on when performing the tasks.[53]

CONCLUSION

The results of the current investigation indicate that patients after ACLR demonstrate altered movement patterns and loading of the involved knee at a time when they were cleared for return to sports. Embedding patients after ACLR in virtual reality changes their movement patterns approximating those of healthy subjects.

Conflict of interest

The authors have no conflicts of interest that are directly relevant to the content of this article.

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