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Curve analyses reveal altered knee, hip, and trunk kinematics during drop–jumps long after anterior cruciate ligament rupture

Kim Hébert-Losier [a,*], Lina Schelin [b], Eva Tengman [c], Andrew Strong [c], Charlotte K. Häger [c]

[a] The University of Waikato, Faculty of Health, Sport and Human Performance, Adams Centre for High Performance, 52 Miro Street, Mount Maunganui, Tauranga 3116, New Zealand
[b] Umeå University, Department of Statistics, Umeå School of Business and Economics, 901 87 Umeå, Sweden
[c] Umeå University, Department of Community Medicine and Rehabilitation Physiotherapy, 901 87 Umeå, Sweden

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ABSTRACT

Background: Anterior cruciate ligament (ACL) ruptures may lead to knee dysfunctions later in life. Single-leg tasks are often evaluated, but bilateral movements may also be compromised. Our aim was to use curve analyses to examine double-leg drop–jump kinematics in ACL-reconstructed, ACL-deficient, and healthy-knee cohorts.

Methods: Subjects with unilateral ACL ruptures treated more than two decades ago (17–28 years) conservatively with physiotherapy (ACL_{PT}, $n = 26$) or in combination with reconstructive surgery (ACL_R, $n = 28$) and healthy-knee controls ($n = 25$) performed 40-cm drop–jumps. Three-dimensional knee, hip, and trunk kinematics were analyzed during *Rebound*, *Flight*, and *Landing* phases. Curves were time-normalized and compared between groups (injured and non-injured legs of ACL_{PT} and ACL_R vs. non-dominant and dominant legs of controls) and within groups (between legs) using functional analysis of variance methods.

Results: Compared to controls, ACL groups exhibited less knee and hip flexion on both legs during *Rebound* and greater knee external rotation on their injured leg at the start of *Rebound* and *Landing*. ACL_R also showed less trunk flexion during *Rebound*. Between-leg differences were observed in ACL_R only, with the injured leg more internally rotated at the hip. Overall, kinematic curves were similar between ACL_R and ACL_{PT}. However, compared to controls, deviations spanned a greater proportion of the drop–jump movement at the hip in ACL_R and at the knee in ACL_{PT}.

Conclusions: Trunk and bilateral leg kinematics during double-leg drop–jumps are still compromised long after ACL-rupture care, independent of treatment. Curve analyses indicate the presence of distinct compensatory mechanisms in ACL_{PT} and ACL_R compared to controls.

1. Introduction

Anterior cruciate ligament (ACL) injuries are of great concern in orthopedic and sports medicine, and are one of the most common sports-related knee injuries [1]. Given that up to 85% of these injuries occur during non-contact or indirect contact situations, particularly those involving side-cutting, landing, and balancing maneuvers [2], the use of tests that assess dynamic neuromuscular control to prevent and manage ACL injuries is recommended [3]. In particular, examining the quality of movement during

* Corresponding author.
E-mail address: kim.hebert-losier@waikato.ac.nz (K. Hébert-Losier).

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challenging tasks, such as during single-leg hops, step downs, or drop–jumps, is useful in clinical practice to determine the risk of ACL injury [4] or re-injury [5], monitor the rehabilitation process [6], and detect persistent neuromuscular deficiencies following discharge from ACL-rupture rehabilitation [7,8].

ACL ruptures are treated either conservatively using a physiotherapy-based approach (ACL_{PT}) or surgically with ACL reconstruction and physiotherapy (ACL_R). Directly comparing the long-term outcomes between ACL_{PT} and ACL_R is challenging given the difficulty in conducting robust randomized control trials in this area and undertaking follow-up investigations over long periods. On the other hand, cross-sectional studies can provide an insight into the functional outcomes of ACL_{PT} and ACL_R, particularly when compared to control (CTRL) subjects. Results from such studies suggest the presence of compensatory mechanisms and altered biomechanical strategies at the knee in both ACL_R and ACL_{PT} not only during single-leg hopping tasks [9,10], but also during double-leg squatting movements [11]. The presence of such compensatory mechanisms in the short and intermediate term is well established; but much less is known regarding the persistence and the extent of biomechanical coping strategies in the long term. Furthermore, how to best capture and quantify these coping strategies remains challenging given the complexity of multi-joint movement control.

In the ACL literature, clinical biomechanical studies have typically relied on discrete measures to characterize movement patterns [12]. However, singular measures are limited in their ability to capture all the variability and complexity of human movement; hence, alternative data analysis methods, including non-linear dynamics [13] and statistical parametric mapping [14], have been employed to provide additional insights. Compensations or movement deficiencies might be missed if focusing only on peaks or discrete biomechanical variables [15]. Traditional statistical approaches may be appropriate for analyzing discrete measures in the presence of an a priori hypothesis, but analyses of the kinematic curves should be conducted in the lack of the above-mentioned hypothesis [16,17]. Recently, we presented a functional analysis of variance (ANOVA) method based on the interval testing procedure (ITP-based ANOVA) and used it to examine knee-kinematic curves from single-leg hops of ACL_R, ACL_{PT}, and CTRL subjects participating in a larger cross-sectional study (KACL20: "Knee injury — ACL after more than 20 years") carried out in our human movement laboratory. The ITP-based ANOVA is similar to the traditional univariate ANOVA, but allowed us to analyze the entire time-domain of kinematic curves and detect precise time intervals where statistical differences occurred between groups. Persistent deviations in knee movement patterns from the age- and sex-matched CTRL cohort were identified, especially when ACL ruptures were treated conservatively [18]. Using this statistical approach, we were able to analyze more comprehensively knee biomechanics throughout this complex single-leg multi-joint task.

Like the single-leg hop, the double-leg drop–jump task is commonly used for assessing the risk of ACL injury [3,4,19] and re-injury [3,5], as well as detecting neuromuscular deficiencies following ACL-rupture rehabilitation in the short- to middle-term [7,8,20]. The drop–jump task is relatively easy to standardize, and its three dimensional (3D) kinematics demonstrate good-to-excellent inter- and intra-session reliability [21] and are valid indicators of the quality of the landing technique [22]. To the best of our knowledge, the use of drop–jumps to assess individuals more than 20 years after an ACL rupture has not been reported to date. A comprehensive analysis of drop–jump kinematics long after ACL-rupture rehabilitation could provide valuable information on the quality of double-leg dynamic movements and compensatory strategies likely to persist long-term in such individuals, complementing our earlier findings of lasting knee kinematic deviations from controls during one-leg hops in ACL-treated cohorts [18]. The knowledge gained could in turn inform our rehabilitation and retraining programs.

Our aim was to employ an ITP-based ANOVA method to examine double-leg drop–jump kinematics of subjects involved in the KACL20 study, and compare the kinematic curves between and within ACL_R, ACL_{PT}, and CTRL cohorts. In addition to knee kinematics, we wanted to examine hip and trunk kinematics and clinically relevant measures of alignment of the lower extremity to consider the entire kinematic chain and the possibility of alterations in joint kinematics proximal to the knee. Based on our recent study [18] and available literature on drop–jump mechanics following ACL_R [7], we anticipated lesser knee flexion and worse alignment of the lower extremity in both ACL groups compared to CTRL, and the presence of between-leg differences in ACL_{PT} and ACL_R [8]. We also hypothesized that movement discrepancies would be more notable in ACL_{PT} than ACL_R.

2. Materials and methods

2.1. Subjects

The dataset used for this investigation comes from a cross-sectional study (KACL20) that addressed several aspects of knee function in ACL_R, ACL_{PT}, and healthy-knee CTRL subjects [10,18,23]. To meet inclusion, subjects had to be able to complete the physical tests. Subjects were excluded if presenting with a contra-indication to complete the study protocol, such as an ongoing injury or disease affecting their movement ability. Additional exclusion criteria were inflammatory or rheumatic disease, neurological condition, knee or hip prosthesis, or a bilateral ACL injury. ACL subjects who suffered a unilateral ACL injury on average 23 years ago (range 17–28 years) were included. The ACL_R and ACL_{PT} cohorts were treated in two separate hospitals that were adhering to different ACL treatment guidelines at the time of injury. The activity levels, graft types, and rehabilitation protocols of subjects are detailed in full by Tengman et al. [23]. All CTRL subjects considered their knees "healthy".

ACL subjects were examined by an orthopedist and physiotherapist, and radiological exams were performed revealing that most (over 80%) of ACL_R and ACL_{PT} had a moderate-to-high degree of osteoarthritis [23]. A physiotherapist screened all CTRL subjects for history of previous knee injuries and tested the integrity of their knee meniscus and ligaments to ensure appropriate inclusion. The CTRL subjects were recruited to match the age and sex of ACL-ruptured subjects as closely as possible. No radiological exams on CRTL subjects were performed to limit their exposure to radiation.

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