

# Anterior Cruciate Ligament Rupture: Functional Data Analysis of Knee Motion

## *Rottura del Legamento Crociato Anteriore: Analisi di Dati Funzionali dei Movimenti del Ginocchio*

Konrad Abramowicz, Charlotte Häger, Kim Hébert-Losier, Alessia Pini, Lina Schelin, Johan Strandberg and Simone Vantini

**Abstract** Human movement data are traditionally summarized into discrete parameters prior to analysis, only considering certain points in time. Nevertheless, the quantities of interest are smooth functions of time, making it possible to analyse motion data using Functional Data Analysis techniques. We present the analysis of a functional data set, that involved comparing the knee movement patterns during a one-leg hop in individuals suffering from an Anterior Cruciate Ligament injury treated with surgery and physiotherapy ( $ACL_R$ ), with physiotherapy alone ( $ACL_{PT}$ ), as well as uninjured controls ( $ACL_C$ ). We compare our results with the ones of a classical technique focusing on the maximum knee flexion data only, and present the advantages of considering a functional approach.

**Abstract** I dati di movimento umano sono tradizionalmente riassunti tramite alcuni parametri discreti prima di effettuare l'analisi, considerando esclusivamente determinati istanti temporali. Tuttavia, dato che le quantità di interesse sono funzioni regolari del tempo, è possibile analizzarle per mezzo di tecniche di analisi di

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*dati funzionali. Presentiamo l'analisi di un data set funzionale con l'obiettivo di confrontare i movimenti durante un salto con una gamba di individui che soffrono di una lesione al legamento crociato anteriore trattati con chirurgia e fisioterapia ( $ACL_R$ ), con solo fisioterapia ( $ACL_{PT}$ ), e un gruppo di controllo ( $ACL_C$ ). Confrontiamo i nostri risultati con quelli di una tecnica classica che si focalizza nel punto di massima flessione, mostrando i vantaggi di considerare un approccio funzionale.*

**Key words:** Functional Data Analysis, ANOVA, Motion Data

## 1 Introduction

Individuals who had suffered an Anterior Cruciate Ligament (ACL) injury may not always recover completely; and, to avoid re-injury or degeneration, it is vital that ACL-injured patients perform physiotherapy. In recent years the movements (especially while performing hops) of ACL patients have been studied [2, 7, 8], and used as indicators of recovery and readiness to return to previous sporting activities. The aim of this paper is to investigate the knee joint movement patterns during a one-leg hop in three groups using data from a long term follow-up (about 20 years) of individuals who have undergone ACL rupture physiotherapy. The three groups correspond to individuals treated with surgery and physiotherapy ( $ACL_R$ ) and conventionally with physiotherapy alone ( $ACL_{PT}$ ), as well as uninjured controls ( $ACL_C$ ).

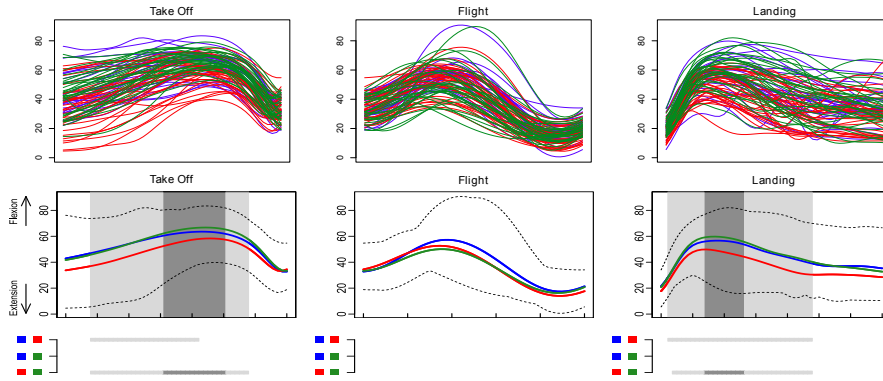
Traditionally, comparison of movements between groups involve selecting particular features of the task, e.g., hop length, maximum knee flexion, or range of motion [7]. Although these features provide an important summary of the movements, they cannot entirely describe the motion. Indeed, human motion involves multiple planes of movement and temporal aspects that may be represented as smooth functions of time and analysed using Functional Data Analysis (FDA) techniques (c.f., [6, 5, 1]).

Thus, we aim to apply a functional ANOVA on motion data, to test whether the movement patterns associated to the three groups of subjects ( $ACL_R$ ,  $ACL_{PT}$ , and  $ACL_C$ ) present statistically significant differences. More importantly, in case of rejection of the null hypothesis of the ANOVA test, we aim at detecting where the possible differences occur to better comprehend in which particular time intervals of the task groups differ. Finally, we also want to determine which groups differ from one another. All these informations are of crucial importance for the data analysis we will carry out, and will provide practitioners with a clear understanding of the movement patterns and potential deficits from ACL injuries. For this purpose, we will apply a non-parametric methodology recently proposed for testing functional data that enables the selection of the intervals where statistically significant differences are observed, that is the Interval Testing Procedure (ITP) [4].

## 2 Analysis of the Knee Joint Movement Data

The data set that we analyse is composed by the knee joint movement patterns of 88 individuals of the three groups (26  $ACL_R$ , 33  $ACL_{PT}$  and 29  $ACL_C$  individuals) during a one-leg hop. In this particular study, all individuals jumped horizontally as far as possible on one leg in a controlled fashion. The time-varying movements of the knee joint of each individual were recorded with a 3-D motion analysis system (Qualisys AB, Sweden). In this work we focus on the flexion-extension angle of the injured leg (for the  $ACL_R$  and  $ACL_{PT}$  groups) and the non-dominant leg (for the  $ACL_C$  group). An extended analysis considering a wider range of data, including different angles and data for the two legs of each subject, is ongoing.

The data (shown in the top panels of Figure 1) are presented and analysed for the three phases of the hop, i.e., the take off (0.7 seconds before the take-off instant), flight (from the take-off instant to the landing instant) and landing segment (0.7 seconds after the landing instant). The data of the flight phase were aligned with an affine transformation to have the same take-off and landing instants for each individual.



**Fig. 1** Top: knee motion data for the three segments, divided into the three groups:  $ACL_R$  (blue),  $ACL_{PT}$  (red) and  $ACL_C$  (green); bottom: means of the groups (solid lines) and range of the data (dashed lines) with significant intervals at a 5% level (light grey) and at a 1% level (dark grey) for the three group-comparison (graphic area) and for the two-group comparisons (lower part).

The bottom panels of Figure 1 report the result of the analysis for the three phases. We represent the three functional means associated to the  $ACL_R$  (blue solid line),  $ACL_{PT}$  (red solid line) and  $ACL_C$  (green solid line) groups. The dashed lines represent the range of the whole data set. The grey area of the graph indicates the intervals selected as significantly different by the ITP with a 5% level (light grey) and 1% level (dark grey), respectively. In line with previous results [8], no significant differences in the flight phase are determined. Moreover, the ITP detects as significantly different an interval of the take-off phase (i.e., from 0.595 seconds to 0.133

seconds before the take-off instant at a 5% level), and an interval of the landing phase (i.e., the interval from 0.042 seconds to 0.476 seconds after the landing instant). In both cases, the significant intervals occur in the area of the maximum knee flexion, with the individuals treated conventionally with physiotherapy only (red lines) apparently having a lower knee flexion compared to the other two groups. The results from the pairwise group comparisons reported below the bottom panels support the latter statement. Indeed, they demonstrate that the  $ACL_{PT}$  group differs from both the  $ACL_R$  (with a lower significance) and the  $ACL_C$  (with a higher significance) groups. On the other hand, the  $ACL_R$  and  $ACL_C$  groups do not differ significantly in terms of their movement patterns. Similar analyses have been carried out with data of the take-off and landing phases aligned with respect to the maximum knee flexion, obtaining consistent results.

A classical parametric ANOVA of the data, considering only the maximum knee flexion in the take-off and landing phases, and the maximum and minimum knee flexion in the flight segment, gives the following results:

- the maximum knee flexion during the take-off is significantly different between groups, with the  $p$ -value of the F test being equal to 0.0015;
- the maximum and minimum knee flexion during flight are not significantly different between groups at a 5% level, with  $p$ -values being respectively 0.087 and 0.16;
- the maximum knee flexion during landing is significantly different between groups, with  $p$ -value equal to 0.0012.

A non-parametric univariate ANOVA based on permutation tests [3] leads to the same conclusions.

These results confirm the findings from the functional approach, i.e., a significant difference between groups during the take-off and landing phases. However, the classical analysis of the maximum knee flexion does not in any way explore the entire data set, but only some of its features. For instance, it indicates that the maximum flexion at the take-off is different between groups, but this does not indicate whether the entire take-off phase differs, or that the difference occurs only at the proximity of the maximum knee flexion instant. The FDA approach, on the other hand, enables us to understand this, i.e., if and how the groups differ in their movement patterns

Indeed, thanks to the ITP, we are able to perform statistical tests that consider the whole curves instead of selecting given points, determine the exact time-intervals that present a significant difference between the groups, and identify the groups that are different from each-other. The analysis that we perform does not only inform us that the groups have different movement patterns, but provides also the exact time intervals when the different movements occurs. Finally, we are able to identify that the differences in these time intervals are mainly due to a distinct movement patterns in the subjects treated conventionally with physiotherapy only, that tend to have lesser knee flexion angles with respect to the ones that underwent surgery and the uninjured controls.

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