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Motor coordination during gait after anterior cruciate ligament injury: a systematic review of the literature★

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ABSTRACT

To investigate the state of art about motor coordination during gait in patients with anterior cruciate ligament (ACL) injury. Searches were carried out, limited from 1980 to 2010, in various databases with keywords related to motor coordination, gait and ACL injury. From the analysis of titles and applying the inclusion/exclusion criteria 24 studies were initially selected and, after reading the abstract, eight studies remained in the final analysis. ACL deficient patients tend to have a more rigid and less variable gait, while injured patients with ACL reconstruction have less rigid and more variable gait with respect to healthy individuals. The overall results suggest the existence of differences in motor coordination between the segments with intact and those with injured knee, regardless of ligament reconstruction. ACL injured patients present aspects related to the impairment of the capability to adapt the gait pattern to different environmental conditions, possibly leading to premature knee degeneration. However, the techniques used for biomechanical gait data processing are limited with respect to obtaining information that leads to the development of intervention strategies aimed at the rehabilitation of that injury, since it is not possible to identify the location within the gait cycle where the differences could be explained.

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Coordenação motora durante a marcha após lesões no ligamento cruzado anterior: uma revisão sistemática da literatura

Palavras-chave:
Biomecânica
Destreza motora, ligamento cruzado anterior/lesões
Marcha

RESUMO

Investigar o estado da arte acerca da coordenação motora durante a marcha em pacientes com lesão no ligamento cruzado anterior (LCA). Foram realizadas pesquisas, delimitadas entre 1980 e 2010, em diversas bases de artigos com palavras-chave relacionadas à coordenação motora, marcha e lesão no LCA. A partir da análise de títulos e aplicação dos critérios de inclusão/exclusão, 24 estudos foram selecionados inicialmente e, após a leitura do resumo, oito permaneceram na análise final. Os resultados indicam que pacientes com deficiência no LCA tendem a apresentar uma marcha menos variável, enquanto pacientes com reconstrução do LCA têm uma marcha mais variável, em relação a sujeitos hígidos. Os resultados sugerem a existência de diferenças na coordenação motora entre os segmentos entre sujeitos com e sem lesão no LCA, independentemente da reconstrução ligamentar. Pacientes com lesão no LCA apresentam aspectos relacionados ao comprometimento de adaptar seus padrões de marcha a diferentes condições externas, o que pode levar à degeneração precoce. No entanto, as técnicas usadas pelos estudos para o processamento dos dados biomecânicos foram limitadas no que diz respeito à obtenção de informações que possibilitem o desenvolvimento de estratégias de intervenção voltadas para a reabilitação da lesão. Isso se deve ao fato de as técnicas atuais de estudo da coordenação motora, apesar de possibilitar a identificação de alterações no padrão de marcha saudável, não serem capazes de identificar as principais articulações e fases do ciclo da marcha alteradas.

Introduction

It has been estimated that 95,000 cases of anterior cruciate ligament (ACL) injury of the knee occur every year in the United States, which gives rise to healthcare expenditure greater than US$ 650 million over the same period.[1] The incidence is greater among individuals who practice sports like basketball, snow skiing, American football and soccer. Taking frequencies of sports participation into account, this injury occurs 2.4 to 9.7 times more frequently among women than among men.[2]

In addition to functional alterations, ACL injuries have been correlated with other important comorbidities. According to Lohmander et al.,[3] between 50% and 100% of the individuals with deficiencies in this ligament will present pain, functional limitations and radiographic signs of knee osteoarthritis 12 to 20 years after the occurrence of the injury.

ACL reconstruction surgery is widely performed to restore joint stability. However, its role in preventing degeneration of the cartilage and development of osteoarthrosis remain matters of controversy. Fink et al.[4] demonstrated high prevalence of osteoarthrosis after ligament reconstruction and observed that degeneration was present over the first 15 months subsequent to the surgery.[5] Although this comorbidity was shown to be more frequently related to joint cartilage damage caused by the initial trauma or subsequent episodes of knee instability, other studies suggested that it could result from kinematic alterations to gait that persist after the surgical procedure and rehabilitation.[6,7]

In this regard, there are suspicions that gait abnormalities could also result from post-injury impairment of the quality of ACL participation in achieving sensory afferences, which would tend to attenuate the information feedback relating to joint position and acceleration between the ligament and the central nervous system. This impairment of the capacity to obtain sensory information relating to the ACL may result in generation of changes to motor coordination patterns during gait.[8]

Bernstein[9] defined motor coordination as the domain of redundant degrees of freedom of a biokinematic chain (BKC) for producing controlled movement. Although each element of the BKC can carry out movements independently, the relationships between the motor actions of the different segments determine the motor coordination needed for each task.

According to Todorov and Jordan,[10] one of the strategies used by the central nervous system (CNS) for achieving conformity of the motor coordination pattern during gait consists of allowing a given amount of variability in angular behavior, through covariation of movements of the BKC segments of the lower limbs, such that they compensate for the individual alterations presented. The coordination strategies encompass not only modulation of the degrees of freedom of each joint of the BKC, but also changes to the variability and stability of motor action movements.[11] Thus, studies addressing motor coordination generally relate to aspects of this like inter and intra-segmental coordination[12,13] and variability.[14]

Unfortunately, although this type of motor coordination is only observable with regard to the behavior of the BKC, it is suspected that there is tendency in studies on gait in patients with ACL injuries to only focus on certain characteristics in isolation, such as the biomechanical behavior of each joint as an independent functional unit.[15-17]

Consequently, there is a scarcity of information on strategies for adaptation of the motor coordination that are implemented in the BKC in order to functionally compensate for the lack of original ligament. Comprehension of these strategies might partially explain the process of early knee joint degeneration after injuries to this ligament and contribute towards improving the delineation of therapeutic approaches. Thus, the aim of this study was to conduct a systematic review of the literature on motor coordination of the lower limbs during gait, among patients with ACL injuries.

Methods

Reports on studies conducted on human beings, in which aspects of lower-limb motor coordination during gait performed by patients with ACL injuries, with or without surgical reconstruction, were selected. The aspects of motor coordination examined included intersegmental coordination,[12,13,18] variability[19,20] and stability/flexibility of the joints during gait.[11,21] Systematic review studies, meta-analyses and studies investigating intervention strategies for rehabilitation after ACL injuries were excluded from this review.

The search was delimited between January 1980 and December 2010, thus covering 30 years of production. The Pubmed/MEDLINE, SciELO, OVID, LILACS, ISI Web Knowledge, Embase, Sportdiscus, Scopus, Cochrane Library and Cinahl databases were consulted. With the aim of enabling a more sensitive and more specific search, combinations of the following keywords were used: *ACL, anterior cruciate ligament, gait, coordination* and *variability.*

All the totals and abstracts initially selected were indexed in the Endnote version 9 software (Thomson Reuters, Carlsbad, USA), for subsequent analysis. The titles and abstracts were examined by two independent examiners. In cases of doubt in selecting articles based on the content of the abstract, the complete article was analyzed. Discrepancies between the examiners were resolved by means of reaching a consensus. In cases in which no consensus was reached, a third examiner was consulted and, based on this opinion, which was given without prior knowledge of the examinations already undertaken, it was decided whether or not to include the manuscript (Fig. 1).

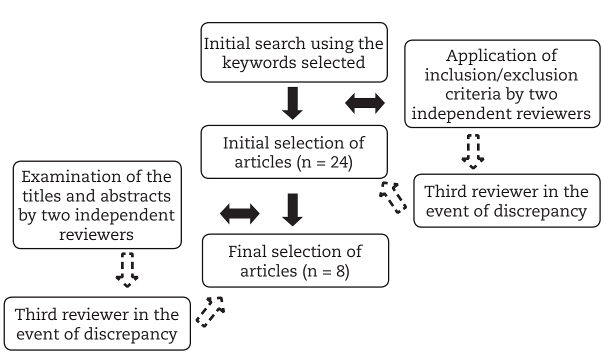

Figure 1 – Flow diagram explaining the study selection process in the systematic review. The dashed arrows represent the possible paths in the event of discrepancy between the first two examiners.

Results

From the initial search, 24 manuscripts were identified. From examining the titles and applying the inclusion and exclusion criteria, eight studies were selected. After reading the abstracts, all of these were retained (Table 1). Of these, it was seen that seven studies used nonlinear techniques for evaluating the variability of knee movement in the sagittal plane during gait, of which four used Lyapunov's exponent technique (ExLy),[22-25] two used approximate entropy (EnAp)[26,27] and one used the differential entropy technique (EnDif).[28] The remaining study, by Kurz et al.,[29] used a continuous relative phase technique (CRP), based on representation of angular velocity to measure the intersegmental coordination.

With regard to ExLy, three studies compared patients with ACL deficiencies with control groups,[22,23,25] and one compared patients with ACL reconstruction using different types of graft with a control group.[24] The dependent variable in all these four studies was ExLy, which was obtained from the angular displacement of the knee in the sagittal plane, during gait performed on a treadmill, although Zampeli et al.[25] used backward gait to compare the groups.

The results from the studies showed that the injured knee presented higher ExLy values than the contralateral knee, both in conventional gait and in going backwards. However, both knees with ACL deficiency showed lower ExLy than in a healthy group. Regarding the ACL-P group, the injured knee presented lower ExLy values than the contralateral knee. Both knees in the ACL-R group, independent of the type of graft, presented higher ExLy values than in a healthy group.

The studies that used EnAp to calculate the variability of the gait[26,27] also used the angular displacement of the knee as a dependent variable. The study that compared a healthy group with an ACL-D group[27] found lower EnAp values for the injured knee than for the uninjured contralateral knee. The other study that used this technique compared two groups with ligament reconstruction, comprising one with a graft from the patellar tendon and another with a graft from the tendon of the knee flexors, with a control group. Independent of the graft used, the ACL-R group presented higher EnAp values than in the control group.

Tzagarakis et al.[28] used an adaptation of EnAp, called EnDif. They compared the frequency spectrum of trunk accelerations between an ACL-R group and healthy individuals, and found higher EnDif values on the mediolateral axis for the ACL-D group, in comparison with the controls. The test used showed a capacity to discriminate 96.5% of the participants in relation to the presence of ligament injury.

Kurz et al.[29] compared the intersegmental coordination relating to angular displacement and to thigh, lower leg and foot velocities, in the sagittal plane, in an ACL-D group and a control group, using the CRP technique. These authors showed that patients with ACL deficiencies presented larger phase angles in relation to lower leg and foot coordination, and smaller values in relation to coordination between the thigh and lower leg, in comparison with the control group.

Table 1 – Description of the eight studies selected for the systematic review.

Authors	Sample	Motor task	Biomechanical variable	Technique	Results
Stergiou et al.[22]	10 ACL-D (3 years after injury)	Gait (treadmill) (0.78 m/s)	AD of the knee (sagittal)	ExLy	Greater ExLy in injured lower limb than in healthy limb, at all velocities. Without influence from velocity.
Moraiti et al.[23]	7 ACL-D (3 years after injury) and 7 C	Gait (treadmill) (ACL-D: 0.74 m/s and C: 0.75 m/s)	AD of the knee (sagittal)	ExLy	Smaller ExLy in ACL-D in relation to group C.
Moraiti et al.[24]	6 M ACL-R-TP (2 years after operation), 6 M ACL-RST (2 years after operation) and 6 M C	Gait (treadmill) (ACLR-TP: 0.86 m/s; ACL-RST: 0.90 m/s and C: 0.91 m/s)	AD of the knee (sagittal)	ExLy	ACL-R-TP and ACL-R-ST presented higher ExLy values than control group.
Zampeli et al.[25]	15 M ACL-D (8 months after injury) and 11 M C	Backward gait (treadmill) (ACL-D: 0.46 m/s; C: 0.55 m/s)	AD of the knee (sagittal)	ExLy	The two lower limbs of the ACL-D presented lower ExLy than in the control group. The uninjured knee of the ACL-D presented lower ExLy values than the injured knee.
Georgoulis et al.[26]	10 ACL-D (3 years after injury)	Gait (treadmill) (0.77 m/s)	AD of the knee (sagittal)	EnAp	Lower EnAp in the injured lower limb than in the uninjured limb, at all velocities. The greater the velocity was, the greater the EnAp was in both groups.
Moraiti et al.[27]	6 M ACL-R-TP (2 years after operation), 6 M ACL-R- ST (2 years after operation) and 6 M C	Gait (treadmill) (ACLR-TP: 0.86 m/s; ACL-RST: 0.90 m/s and C: 0.91 m/s)	AD of the knee (sagittal)	EnAp	ACL-R-TP and ACL-R-ST presented higher EnAp values than in the controls. Injured lower limb presented lower values in relation to the uninjured contralateral lower limb in both groups.
Tzagarakis et al.[28]	20 M ACL-D and 20 M C	Gait (track of 40 m)	FFT of trunk acceleration	EnDif	Higher EnDif values in ACL-D for the frequency spectrum of the medial-lateral axis, in relation to group C. Test presented 96.5% discrimination between patients with and without ACL injury.
Kurz et al.[29]	10 ACL-R (3.5 years after operation) and 10 C	Gait (treadmill) (ACL-D: 1.21 m/s, C: 1.23 m/s)	CRP of the thigh, lower leg and foot (sagittal)	CRP	ACL-R presented greater phase angle in the foot-lower leg relationship and lower in the lower leg-thigh relationship, than in group C.

ACL-D, anterior cruciate ligament deficient; ACL-R, anterior cruciate ligament reconstruction; C, Control; M, Male, F, Female, AD, angular displacement; ExLy, Lyapunov's exponent; CRP, continuous relative phase technique; EnAp, approximate entropy; EnDif, differential entropy.

Discussion

In this investigation, we proposed to systematically review the state of the art regarding knowledge production on aspects of the lower-limb motor coordination of patients with ACL injuries, during gait. We observed that the motor coordination of lower-limb gait among patients affected by ACL injuries is a topic that has been little explored within the context of scientific investigations, which made meta-analysis impossible. The main limitation found in the present review was that most of the studies were undertaken by the same research group.[22-27,29] This may have led to bias in interpreting the results from the articles selected.

Despite this limitation, the biomechanical data relating to coordination strategies for the lower limbs during gait were processed by means of four techniques: approximate entropy (EnAp), Lyapunov's exponents (ExLy), differential entropy (EnDif) and continuous relative phase, based on the variability of the data, thus quantifying the regularity or predictability of systems that change with time.[30] Measurements of the likelihood that a given segment of the temporal series might predict the configuration of another segment of the same data series are made. Higher coefficients indicate greater irregularity and greater complexity, while lower values reveal greater regularity, predictability and periodic behavior.[30]

ExLy is another nonlinear measurement strategy that enables measurement of the sensitivity of the system to the initial conditions and the amount of instability or predictability of a system.[30] Presence of positive ExLy indicates chaos, while there is a tendency towards values close to zero in linear systems. Higher values have been correlated with chaotic behavior and linearity shows a tendency towards the value zero.

The CRP technique uses angular velocity analysis in which the Cartesian coordinates (x,y) relating to each point on the curve are transformed into polar coordinates (r,θ). The polar phase of each point on the curve is used to calculate the dynamic interaction between the two segments, such that the variable of interest is the algebraic difference between the polar phase of one distal segment and that of an immediately proximal segment, for example the difference between the lower leg and the thigh (θ [lower leg] – θ [thigh]) or between the foot and the lower leg (θ [foot] – θ [lower leg]).[18] In this technique, values close to 0° indicate that the two segments are moving in a convergent manner, which characterizes in-phase coordination, while values close to 180° indicate that the segments are moving in a divergent manner, which characterizes out-of-phase coordination.[31] In order to make it possible to statistically test the new values generated in each comparison, the absolute arithmetic mean of each of these curves is used.

With regard to the results, the study by Kurz et al.[29] showed that the intersegmental coordination of both the knee and the ankle were altered in patients with ACL reconstruction, in relation to healthy individuals. The difference in the CRP of the thigh in relation to the lower leg was more pronounced in the final support phase, in which the ACL-R group presented coordination with greater out-of-phase characteristics in relation to the control group. The results indicated that the thigh moved more rapidly in relation to the lower leg in the ACL-R group, thus differing from what was seen among the healthy individuals. The magnitude of the peaks of the CRP curve formed by the lower leg and foot was different between the groups, even though the events occurred at times close to each other. The different strategies used by the patients with ACL-R may have increased the loads imposed on the knee, thereby altering its stability.[8] These factors may have a long-term effect that may lead to osteoarthritis in the joint.[29] This study proved that even if the injury site was the knee joint, other joints in the BKC altered their behavior secondarily, which confirms the importance of proceeding with evaluations on all the joints of the lower limbs when examining patients with ACL injuries.[29]

The studies that used nonlinear techniques generally obtained similar results. Patients with ACL deficiencies without surgical reconstruction presented gait patterns that were more rigid and less variable, while those with ligament reconstruction presented greater variability than healthy patients. These findings may be related to the fact that before the surgical procedure, the mechanical instability caused by the ligament deficiency led to greater restriction of movements, either due to insecurity or due to the pain presented in this phase. According to Solomonow,[32] the proprioception system becomes damaged through the reconstruction, due to both the injury and the surgical procedure. This compromises the sensory feedback relating to the ligament-muscle reflex, and probably results in deterioration of the capacity to identify joint position and velocity, thus giving rise to a greater degree of kinematic variability during the gait process.

Diminution of an optimum state of variability (which has been described as the variability of healthy individuals) makes the system more rigid, whereas an increase in relation to the optimum state makes the system more unstable and more susceptible to perturbations.[33] By establishing a parallel with studies on signs, it can be seen that both situations indicate that the system is less adaptable to perturbations and necessities imposed by the environment, and are therefore directly related to reduction of health status. This has already been identified for other types of sign, such as cardiological signs[34] and neural signs.[33]

The results from the studies analyzed showed that when the two lower limbs in the ACL-D group were compared, the intact side of the ACL-D group presented gait that was more regular and less variable than the injured side.[22,23,25] According to Georgoulis et al.,[26] this characteristic attenuates the adaptability of the system and leaves it less capable of adjusting the joint position to deal with external perturbations. This may explain the high prevalence of degenerative joint diseases in injured knees, over long-term follow-up.

These results were seen under different analysis conditions. While most of the studies examined conventional gait, Zampelli et al.[25] found the same results as described above (Table 1) in backwards gait. This approach is greatly used within the sphere of rehabilitation, given that there is evidence that the posterior muscles of the thigh are activated more during this motor task. Tzagarakis et al.[28] used an accelerometer positioned at trunk level to measure the variability of acceleration along the medial-lateral and anteroposterior axes and found similar results (Table 1).

Another characteristic compared was the variability in gait between groups with ligament reconstruction using different types of graft. Moraiti et al.[24,27] found that individuals treated with grafts either from the patellar tendon or from the flexor tendons presented higher values for EnAp and ExLy than seen in the healthy group. However, comparison between the different types of graft did not show any differences. This may partially explain the similarity of the results regarding development of osteoarthrosis, among patients undergoing ligament reconstruction using either of these two techniques.[36]

Moraiti et al.[24] also observed that the intact limb in the ACL-R group presented higher ExLy values than in the injured limb. These results suggest that the healthy lower limb of individuals with unilateral ACL injury presents alterations in relation to the injured limb, even after full reestablishment of functional status. This also suggests that the healthy limb of the ACL-R group presents a gait pattern that is more rigid than that of the injured limb. These authors explained these findings by using the argument that these differences may have occurred through compensatory mechanisms that were generated with the aim of maintaining a certain degree of symmetry between the two lower limbs.[24]

Although nonlinear processing techniques are very useful for identifying individuals' overall motor coordination status, it is not possible to identify which phase of the temporal series is responsible for generating the increase or decrease in variability, because the results are described solely as coefficients. Thus, the possibilities of practical interpretation and consequent development of new therapeutic strategies for retraining the gait pattern, based on these results, are limited. To surmount the limitation presented above, other processing techniques for the space-time representations of multidimensional signs have been used in studying gait. One of the most used methods is principal component analysis,[37] which not only allows complete analysis on the temporal series but also enables identification of the main location responsible for the variability between the groups, through studying the load factors present in the eigenvectors of the principal components.[38,39]

Other limitations are also presented in the studies, particularly in relation to the types of instruments used for the tests and the population studied. With regard to the instruments used, eight of the nine studies (Table 1) used treadmills to record gait. The authors explained that gait data were gathered from treadmills because of the need to collect information on a large number of consecutive paces, which made this impossible to do on a track. Moreover, they alleged that using a track might give rise to the possibility of gait velocity variation between the groups. In fact, evidence that gait velocity affects the variability of the data does exist.[40] On the other hand, use of treadmills does not perfectly reproduce the day-to-day gait pattern. Regardless of the influence of velocity on gait variability, the alterations are what is present in daily activities. It is important to devise processing and interpretation systems that also consider these to be determinant variables relating to the final results. Furthermore, the explanation that use of a treadmill was based on the need to record a large number of consecutive steps does not seem to us to be adequate, given that this procedural demand can be met through using other techniques such as gyroscopes, which present proven validity and reliability with low error rates, particularly in examinations in the sagittal plane.[16] In relation to the population tests, all the individuals with ACL deficiencies (ACL-D) were classified as ligament-dependent, i.e. non-copers. In this regard, Rudolph et al.[41] showed that copers and non-copers present different functional characteristics. Therefore, the results presented in this review should be limited to individuals classified as non-copers. There is a need for further studies in order to make inferences regarding the structure of gait variability for the population that is not ligament-dependent, i.e. individuals who are copers.

We suggest that future studies should investigate associations between these techniques and coordination measurements, with practical interpretation such as intersegmental coordination, measured from angle-to-angle representations, with data processing procedures that make it possible to identify alterations and interpret the full time series, such as principal component analysis or artificial neural networks.

Final remarks

From the results of the studies, it can be concluded that there were two situations: (1) independent of surgical restructuring, patients with ACL injuries present characteristics of lower capacity to adapt their gait pattern to different environmental conditions, such that the ACL-D group presented gait that was more rigid and less variable, while the ACL-R group presented gait that was less rigid and more variable, in relation to healthy individuals; (2) there were differences in behavior between intact and injured knees, both in the ACL-D and in the ACL-R group; and (3) the processing techniques in the studies found (Lyapunov's exponents, approximate entropy and continuous relative phase) only made it possible to conclude that there were alterations in gait patterns. It was not possible, from the techniques used, to conclude that the gait phase was altered, which makes it difficult to develop new therapies specific for rehabilitation. Moreover, it is not known whether these alterations are related to development of knee osteoarthritis.

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Conflicts of interest

The authors declare no conflicts of interest.

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