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A novel approach for the detection and exploration of joint coupling patterns in the lower limb kinetic chain

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ABSTRACT

Background: A comprehensive perspective on foot and lower limb joint coupling is lacking since previous studies did not consider the multi-articular nature of the foot and lower limb neither accounted for biomechanical heterogeneity.

Research question: The current manuscript describes a novel methodological process for detection and exploration of joint coupling patterns in the lower limb kinetic chain.

Methods: The first stage of the methodological process encompasses the measurement of 3D joint kinematics of the foot and lower limb kinetic chain during dynamic activities. The second stage consists of selecting the kinematic waveforms of interest. In the third stage, cross-correlation coefficients are calculated across the selected one-dimensional continua of each subject. In the fourth stage, all cross-correlation coefficients per subject are used as input variable in a cluster algorithm. Algorithm specific qualitative metrics are subsequently considered to determine the most robust clustering. Finally, in the fifth stage the process of biomechanical interpretation is initiated and further exploration is recommended by triangulating with other biomechanical variables.

Results: A first clinical illustration of the novel method was provided using data of fourteen young elite athletes. Cross-correlation coefficients for each leg were calculated across continua of the pelvis, hip, knee, rear foot and midfoot. A hierarchical clustering approach stratified the coefficients into two distinct clusters which was mainly guided by the frontal plane knee kinematics. Both clustered differed significantly from each other with respect to their frontal plane ankle, knee and hip kinetics.

Significance: The presented method seems to provide a valuable approach to gain insight into foot and lower joint coupling.

1. Introduction

Despite advances in rehabilitation and secondary prevention strategies, recurrence rates of running-related injuries remain high [1,2]. Many studies aimed at establishing risk factors for these high recurrence rates and these have traditionally been divided into two main categories: intrinsic (or athlete-related) risk factors and extrinsic (or environmental) risk factors. Intrinsic risk factors encompass, among others, excessive rear foot motion, poor dynamic joint stabilization, inadequate postural control and reduced coordinative variability [3–6]. An integrated assessment or screening of the athlete has therefore been recommended in order to detect impairments and deficits along the so-called foot and lower limb kinetic chain [7].

The majority of studies in the literature analyzing lower limb biomechanics focused on the kinematics of individual lower extremity joints instead of addressing the interaction between joints. The study of foot and lower limb joint coupling, defined as the (a)synchronous motion between joints as a result of the functional mechanical propagation within the aforementioned kinetic chain, may be of greater interest [8]. This propagation is guided by the anatomy and bone morphology, neuromuscular control and ground reaction forces [9]. The coupling between the foot and lower limb segments has been assessed using correlational analyses [10], with cross-correlations [11,12] and with the dynamic systems approach [9].

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The literature has shown inter-segment coordination between rear foot inversion/eversion and tibia internal/external rotation, rear foot inversion/eversion and forefoot inversion/eversion as well as tibia internal/external rotation and hip internal/external rotation [10,13,14]. The degree of inter-segment coordination was found to be influenced by numerous factors such as step width, running speed, muscle fatigue, muscle strength, mobility, neuromuscular control and previous injury [12,15–17]. It has been theorized that altered or disrupted coupling mechanisms may be one of the multiple etiological factors of musculoskeletal injuries since it would result in pathological joint contact forces and soft tissue stress. Though, there also seems to emerge a general consensus about the presence of considerable joint coupling heterogeneity among injurious and non-injurious populations [18,19]. However, a comprehensive insight is lacking since previous studies did not adopt a kinetic chain approach encompassing segments of both the lower limb and the foot.

The biomechanical community is facing a considerable challenge when it comes to better grasp the aforementioned theories on joint coupling adequately. Understanding the complex linkage between segments of the lower limb will not only provide fundamental insight into the biomechanics of the foot and lower limb, it may also help understanding sub-optimal outcomes associated to non-invasive (e.g. rehabilitation programmes, motor control exercises, footwear, foot orthotics) and invasive treatments (e.g. surgery).

Therefore, our main purpose was to propose a methodological process which may serve as basis for detection of joint coupling patterns along the lower limb kinetic chain. The secondary objective was to provide a clinical illustration of the framework and triangulate this first clinical illustration with foot and lower limb kinetics.

2. Methods

2.1. Methodological process

The first stage of the methodological process encompasses the measurement of 3D joint kinematics of the foot and lower limb kinetic chain during dynamic activities (Additional file 1). The integration of a multi-segment foot model is highly recommended at this stage, since one-segment foot models do not grasp the behavior of the lower limb kinetic chain adequately [20]. The second stage consists of selecting the kinematic waveforms of interest. The latter may be a subjective or objective process, depending on the nature of the research question. In the third stage, cross-correlation coefficients [11] are calculated across the selected one-dimensional continua of each subject (Additional file 1). In the fourth stage, all cross-correlation coefficients per subject are used as input variable in a cluster algorithm. Selection of a cluster algorithm depends again upon the nature of the research question. Algorithm specific qualitative metrics are subsequently considered to determine the most robust clustering. Finally, in the fifth stage the process of biomechanical interpretation is initiated and further exploration is recommended by triangulating with other biomechanical variables (e.g. joint kinetics, muscle activity parameters) (Additional file 1).

2.2. Clinical illustration

2.2.1. Participants

Fourteen young elite athletes (8 female, 6 males; age: mean (SD) = 18.11 (1.21) years; weight: mean (SD) = 60.02 (5.23) kg; height: mean (SD) = 1.78 (0.08) m; body mass index: mean (SD) = 20.77 (1.32) kg/m^2) were selected by the Flemish Athletic League. Athletes had to be free of injury and pain in the legs and lower back for the last 6 months. The Ethical Committee of the University Hospitals Leuven granted ethical approval (S56252/B322201420668).

2.2.2. Equipment (stage 1)

Kinematic data was collected with a passive optoelectronic motion analysis system consisting of 10 T-10 cameras (Vicon Motion System Ltd, Oxford Metrics, UK) which were placed around a 10 m runway. In this runway, a force platform (Advanced Mechanical Technology, Newton, MA, USA) is embedded on which a pressure platform (dimensions 0.5 m × 0.4 m, 4096 sensors, spatial resolution 2.8 sensors per cm^2 RSscan International, Olen, Belgium) is fixed.

Retroreflective markers were positioned on the body of the athletes conforming to the lower-body Plug-In-Gait Sacrum model [21] as well as the Rizzoli Foot model [22]. For calibration purposes, each test session began with capturing a static bipedal trial. Hereafter, athletes were given the instruction to run at their naturally preferred speed along the runway and a minimum of four trials were selected for further analyses. Marker trajectories were captured at 100 Hz whereas force plate and pressure plate data were sampled at 200 Hz.

2.2.3. Data processing and selection (stage 2)

In stage 2, processing of joint kinematics was performed with the Vicon Foot model Plug-in (Aurion Srl, Milano, Italy) and the Vicon Sacrum Plug-in (Vicon Motion System Ltd, Oxford Metrics, UK). Since the Plug-In-Gait Sacrum model is found to be sensitive to kinematic 'cross-talk' [23,24], especially at the knee, the optimization procedure proposed by Baker et al. [25] has been applied. Calculation of the thigh offset as described by Baker et al. [25] was unsuccessful in five limbs. Consequently, the number of data finally decreased to 23 limbs.

For the remaining limbs, three-dimensional lower limb kinetics were subsequently calculated through a full inverse dynamic model and anthropometric data from Dempster [26].

Events associated to a full running cycle were determined by visual inspection as well with a threshold of 20N set on the force platform. The in-house made software ACEPManager was used to perform time normalization of the kinematic data to 100% stance phase.

Finally, kinematic variables of interest were selected. For the current clinical illustration, the following frontal plane variables were considered: pelvic obliquity, hip adduction, knee adduction, rear foot eversion, midfoot eversion. Rear foot adduction was the sole transverse plane variable which was considered. Selection of the aforementioned variables was partially based on previous studies conducted in the field of foot and lower limb joint coupling [12–17] as well as the clinical experience of the authors.

2.2.4. Data analysis (stage 3–4)

Stage 3 consisted of calculating the coefficient of cross-correlation (r_{xy}) [11] across the following stance phase related one-dimensional frontal or transverse plane continua: pelvic obliquity and hip adduction, hip adduction/knee adduction, knee adduction/rear foot adduction, knee adduction/rear foot eversion, rear foot eversion/rear foot adduction and rear foot eversion/midfoot eversion.

In stage 4, a hierarchical clustering approach was used where the aforementioned coefficient of cross-correlation values served as input parameters [27]. The inconsistency coefficient was used to determine the most optimal clustering. The inconsistency coefficient compares the height of a link in a cluster hierarchy with the average height of links below it.

In stage 5, sagittal and frontal plane lower limb kinetic data from the ankle, knee and hip were considered in order to fulfill the second objective of the study. The external moment at initial contact as well as the maximum and minimum value during the peak impact phase (PIP), the absorption phase (AP) and the generation phase (GP) was calculated. Determination of these sub phases was based on the vertical ground reaction force signal (Additional file 2).

The non-parametric Wilcoxon rank-sum test (p value < 0.05) was used to perform inferential analyses between the resulting clusters from stage 4.