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Velocity/curvature relations along a single turn in human locomotion

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Abstract

Neuroscientific approaches have provided an important invariant linking kinematics and geometry in locomotion: a power law controls the relation between radius of curvature and velocity of the trajectory followed. However, these trajectories are predefined and cyclic. Consequently, they cannot be considered as fully natural. We investigate whether this relationship still exists in one unconstrained turn, which can be compared to an everyday life movement. Two different approaches were developed: an intra-individual one along each turn of each trial and an inter-individual one based on a specific instant for which a subject's trajectory goes through its maximal curvature. Eleven subjects performed turns at three gait speeds (natural, slow, fast). The intra-individual approach did not lead to any power law between velocity and curvature along one single trial. Notwithstanding, the inter-individual approach showed a power law between the whole couples "minimal radius of curvature/associated velocity". Thus, the speed/curvature relation is more a "long term" motor control law linked to the turning task goal rather than a "short term" one dealing with trajectory following all the time of the motion.

Keywords: Locomotion; Turning behaviour; Centre of the turn; Power law; Kinematics

Straight-ahead walking has been extensively studied in standardized conditions, such as on a treadmill. Walking under such conditions remains far from everyday life path, and locomotion is a complex function strongly dependent on the desired destination and the presence of obstacles. Indeed, turning is a part of the basic library of motor synergies [3] and Orendurff et al. [12] denote that "the biomechanics of changing direction while walking has been largely neglected despite its obvious relevancy to functional mobility". Nevertheless, several studies, which can be divided into two sets, have considered curved trajectories.

In the first set, one (sometimes two) turn has been studied to highlight comportemental laws which define motor invariants for locomotor trajectories generation. One particular behaviour is the control of head and body orientation while steering [3,4,7,9]. Head deviation toward the future direction anticipates the body shift motion with the "go where we look" strategy, whatever the conditions of vision or speed. This ensures to prepare a stable reference frame [5,14] by finding out about the future direction. The onset of head deviation is initiated at a constant distance rather than a constant time from the corner [14]. Some others studies are interested in the foot placement strategy [6,13]. Finally, in the computer graphics domain, Brogan and Johnson [1] developed a human locomotion model which was created with an a priori knowledge on the environment (i.e. obstacles) thanks to pedestrians video observation in real conditions (offices).

In the second set, human behaviour while steering has been studied on cyclic trajectories which were often pre-defined. In these studies [8,16], the aim was to explore the power law between velocity and curvature previously demonstrated in hand motion [10,18]. This law states that there exists a linear relation between velocity and radius of curvature in the logarithmic space. More precisely, velocity is proportional to the third root of the radius of curvature. To avoid confusion, let us recall that this law can be seen as a relation between curvature (C) and angular speed (Ω) or between radius of curvature (R) and linear speed (V). As, first, $R = 1/C$ and then $V = R\Omega$, a "two-third" Ω/C relation is equivalent to a "one-third" V/R one. Such a relation has been demonstrated for head motion while a subject walks along an elliptic path drawn on the floor [16]. Even if the neural origins of this law are still discussed, Vieilledent et al. [16] explained it by the role of central nervous system which

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computes locomotion strategies according to the shape of the path to follow. In this sense, Hicheur et al. [8] recently suggested that this law is more general and that the actual power value is shape dependent.

This power law is a fundamental result since it provides a motion invariant and helps to better understand the processes governing human locomotion. Nevertheless, this power law has only been demonstrated for cyclic and constrained locomotor trajectories. Such trajectories are never encountered in everyday life. In the first set of studies, working on natural paths, the relation between velocity and geometry has never been studied. Consequently, the first purpose of our study is to check whether such a relationship between kinematics and geometry still exists along a single turn which is an everyday life motion and induces speed and curvature variations.

Studying an unconstrained single turn should provide a new approach to investigate the origin of the velocity/curvature relationship, which could be linked to motor control at two different levels: a “short term” one, the instantaneous trajectory following, but also a “long term” one, the global turning task. Indeed, a locomotor task could be either completed by following a pre-computed trajectory (the main objective of the control being step by step path planning) or by minimising the difference between the original position and orientation and the desired ones (the trajectory is then only the result of this minimisation control).

As we cannot observe any power law in straight-ahead motion before and after the turn, it is primordial to clearly identify the time interval when the subject is actually turning. Indeed, the radius of curvature, despite body periodic lateral oscillations, tends to infinity in particular when oscillation goes from one side to the other (there is a point of inflexion, i.e. an infinite radius of curvature) whereas speed obviously remains bounded. Therefore, we first proposed to define the Key Instant of the Turn (KIT) corresponding to the instant where curvature is maximal. Then, two different ways were considered to explore the power law along a single turn. The first one was an intra-individual analysis of the potential relation between velocity and curvature along time along the turn, following a procedure inspired by the one used by Vieilledent et al. [16]. The second one, inter-individual and original in this study, was to focus on the characteristic point reached at the KIT. The aim was to investigate if a relation between velocity and this maximal curvature exists, not along time, but when considering the set of all those characteristic points for any trial of any subject.

Eleven subjects, five men and six women, volunteered for this experiment. They were 29 years old (±11) (mean ± S.D.) and 1.71 m tall (±0.07). They had no known vestibular or neurological pathology, which would affect their locomotion. Subjects gave written and informed consent and the study conformed to the Declaration of Helsinki.

Subjects, barefoot, performed 90° corner trajectories at three individual gait speeds: natural, slow and fast. For each speed, they performed this simple motion four times: twice on the left and twice on the right. What will be now called a trial is thus one turn at one speed. Between two trials, subjects did fully stop for at least 5 s to ensure a non-periodic motion. Trajectory was not predefined on the floor. Only three markers were put down on the floor to simulate a corner around which subjects had to walk. The aim was to focus on locomotion behaviour for one change of direction.

Three-dimensional kinematic data were recorded thanks to the optoelectronic motion capture device Vicon MX (Oxford Metrics, Oxford, UK). Twelve high-resolution cameras (4 megapixels), at a sampling rate of 120 Hz, formed a circle around the scene. Twenty-eight reflective markers were attached to the subject skin on the following anatomical landmarks: sterno-clavicular joint, xiphoid process, 7th cervical vertebra, 10th thoracic vertebra and for both hemi-bodies, occipital and frontal bones, gleno-humeral joint, lateral humeral epicondyle, ulnar styloid process, radial styloid process, anterior iliospinale, posterior iliospinale, lateral tibiale, lateral malleolus, heel, head of the 2nd metatarsus.

Reconstruction and labellisation were performed using Vicon IQ software (Oxford Metrics) and computations using Matlab 6.5 (Mathworks, Natick, MA). The high quality of acquisitions (static error on marker position is less than 0.1 mm) allowed avoiding using any filtering.

We calculated the body centre of mass (CoM) thanks to Zatsiorsky et al.’s anthropometric table [19]. We calculated the head position, seen as the mean of the four head markers position. Even if we did not expect differences with the CoM, we chose studying the head to compare our power law results with previous studies working on this reference point. Three-dimensional velocity and acceleration were also computed using a classical single or double derivative of the position.

In order to specifically study the adaptation of locomotion while turning, we had to precisely determine when the subjects actually turn, in order to avoid straight parts in their trajectory. We focused on the very characteristic cusp of the evolute of the radius of curvature (Fig. 1). This cusp matched with the minimal radius of curvature, hereafter called Centre of the Turn (CoT). For all trials, we considered the exact instant when this point was reached as the Key Instant of the Turn. Then, by drawing from the CoT, the parallels to the two axes of the turn, we get a quadrant. The beginning and the end of the turn were, respectively, defined

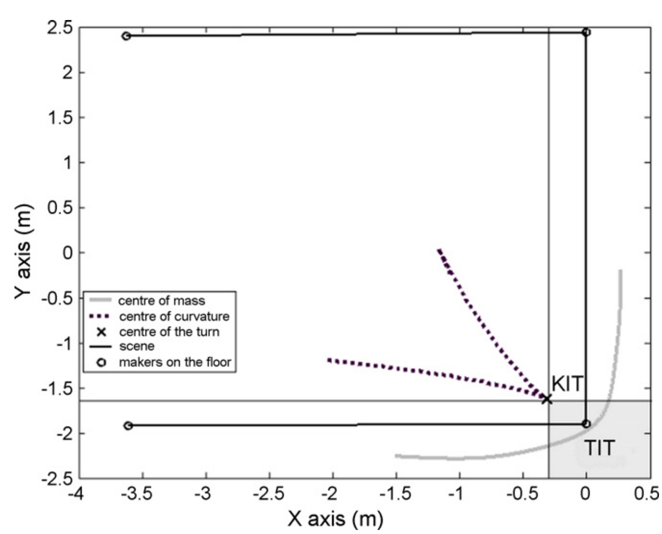

Fig. 1. Evolution of the centre of curvature of the centre of mass trajectory. KIT is the Key Instant of the Turn and TIT is the Time Interval of the Turn.