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The Elusive Stepping Pattern

Pascal Bach[1] Quentin Silvestre[2] Ronan Boulic[2]
[1]Siemens, Zug, Switzerland
[2] IIG, Ecole Polytechnique Fédérale de Lausanne, Suisse
E-mail: Pascal.Bach@a3.epfl.ch, {Quentin.Silvestre, Ronan.Boulic}@epfl.ch

Abstract

Stepping is a class of complex coordinated movements allowing a standing individual to relocate oneself locally with a potentially large body reorientation. Being a key component of numerous higher-level activities, it deserves to be studied for itself. Due to the local nature of the relocation such stepping movement is holonomic, i.e. one exploits fully two degree of mobility of instantaneous translation. This fact clearly contrasts with the sole 1D displacement along the tangent to the body trajectory in the locomotion pattern. Hence, this key difference and the absence of a periodic steady state prevent the analysis of stepping as a variant of the locomotion pattern. In this paper we present a method for recording and analyzing a wide range of stepping movements including two to five steps and re-orientations up to 135°.

1. Introduction

We define the stepping activity as the performance of a few steps for relocating the body locally in position and orientation. Such an activity is necessary for the correct achievement of many other higher-level daily functional activities. The locality of the body relocation is the key characteristic that makes stepping different from locomotion. In particular, the short duration and the transition from and to a rest state produce an irregular non-periodic joint activation. Moreover stepping displays holonomic 2D translation displacements instead of the nonholonomic 1D tangent translation in the sagittal plane observed in locomotion [1][7]. For these reason the large body of work available on locomotion is of little help for modeling and simulating stepping.

In the present paper we describe a first attempt at modeling this activity [2]. First a model is proposed based on recent works in Robotics [6] exploiting an Inverse Kinematics solver [3]. This model is used to determine a sampling of position/orientation targets for a small experimental study. The next section describes an original setup introduced for the reliable measurement of stepping. The following section presents experimental results and compares them with the predictions of the model. The last section identifies directions for future experiments.

2. Background

The study of human displacements has often been performed over treadmills or in motion capture corridors, but seldom in environments that better reflect the context of human daily activities. Fajen and Warren were among the first to analyze steering trajectories towards a position goal or when avoiding an obstacle [4]. More recently, studies on long distance body relocation with prescribed final orientation have confirmed the nonholonomy hypothesis of locomotion trajectories [5], [1]. During these experiments, subjects were asked to pass through start and destination porches at natural walking speed. The distances between porches were in the range of [2.5, 8] meters with various relative orientations. The starting point was always the same while the target location was randomly selected at each trial. Optical markers placed on the body were used to deduce the body torso orientation and the foot trajectories. From this information the stereotyped nature of long-distance locomotion trajectories was revealed; in particular the fact that the body sagittal plane was always tangent to the trajectory. This property, known as nonholonomy, means that the body moves as if it could only perform a 1D translation along the trajectory tangent, i.e. like a wheelchair. On the other hand, the high variability of feet placement across repetitions made unlikely the hypothesis that goal-oriented locomotion is planned as a succession of steps [5]. In 2010, Truong studied even closer relocations within [0.5, 3] meters, with null start and end speed [7]. He noticed that the nonholonomy property does not hold any more during the transition phase to the chosen natural speed. Within the shortest distance ranges the subjects were clearly exploiting a 2D translation ability. Moreover, on the contrary to [5] for longer relocations, Truong reports the observation of only one type of foot placement for each target (section 4.7.4 in [7]).

Our objective is to deepen this observation on the existence of a foot placement pattern for stepping and to propose a model for short range full body relocation. We were inspired by an Inverse Kinematics technique used in Robotics for predicting a sequence of feet placements for a humanoid robot HRP2 [6]. A description of the IK solver we exploit can be found in [3].

3. Step Prediction Model

Kanoun et al. proposed to model a step sequence as an articulated chain where each step location is viewed as a joint with three degrees of mobility with respect to the previous and to the next step [6]. The displacement between two steps is modeled with a 2D translation. Given such a chain with a fixed number of steps, they were able to converge to a solution representing a path between two locations in the 2D plane.

We have adopted a similar approach [2] except that we prefer to model the relative displacement of the next step with 2 polar degrees of mobility (φ,D), i.e. one rotation orienting the line linking the two steps and one translation along this line. Like in [6], this is completed with an additional local rotation Δ of the next step (Fig. 1). We can better specify the inequality constraints on successive steps with this parameter set.

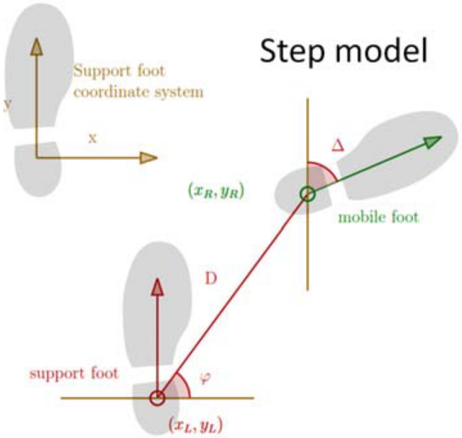

Fig. 1: Local coordinate system associated to the support foot and polar degrees of mobility (φ, D, Δ).

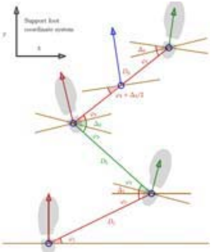

Fig. 2: a chain composed of 3 steps and highlighting the final body orientation defined as the last mid-feet orientation

For a given chain with a fixed number of steps the main tasks of the inverse kinematics solver is to bring the body to the target location (the body state is approximated as the mid-distance and mid-orientation of the last two feet locations as visible on Fig.2). The main task is subject to inequality constraints on the step length and angles. The step chain being redundant, an additional comfort cost function is optimized in the Null space of the main task Jacobian. This cost function includes three terms, each trying to bring the step parameters (φ,D, Δ) closer to a set of values characterizing the standing rest pose. In addition the final step is weighted to give it a greater importance compared to the intermediate steps. A constant cost is added for each step for later comparisons when the same target is reached with different numbers of steps (from 1 to 6). Its purpose is also to identify the step chain with the lowest cost for each target.

We have run the optimization for target points every 5% of the leg length (denoted L) within a 2*L side square in the 2D plane, the starting position being in the middle of the square. For each of these points we have evaluated the relative target orientations every 22.5° between 0° and 180°. Figure 3 displays the chain with the optimal number of steps when the target orientation is the same as the initial orientation (i.e. 0°). Blue means 2 steps, green means 3 steps, etc.

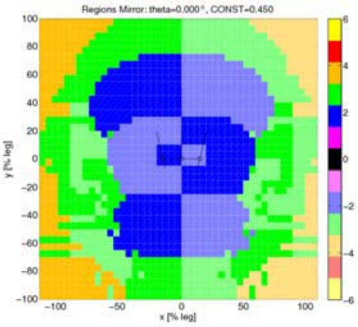

Fig. 3: predicted optimal number of steps (0° relative orientation)

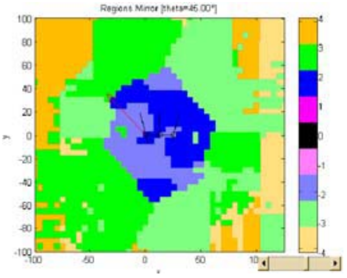

Fig. 4: predicted optimal number of steps (45° relative orientation to the left)

4. Experimental Target Sampling

The model predictions suggest that large areas of the plane will trigger a homogenous pattern with the same number of steps and the same starting foot (illustrated on Fig.3 & 4 with a different shade of the same color). However they suggest also some more chaotic regions as in the green bottom part of Fig 3. For relative target orientations different from 0° the predictions are no more symmetric with respect to the initial sagittal plane (e.g. 45° to the left in Fig. 4). The shape of homogeneous stepping patterns varies greatly too. Making an experiment with subject with the same sampling density is not possible due to the high number of targets (25600). For this reason, based on the predictions, we have retained a smaller set of 150 targets that would likely be centers of homogeneous stepping pattern areas for the chosen orientations (Fig. 5, the initial orientation is vertical in the middle).

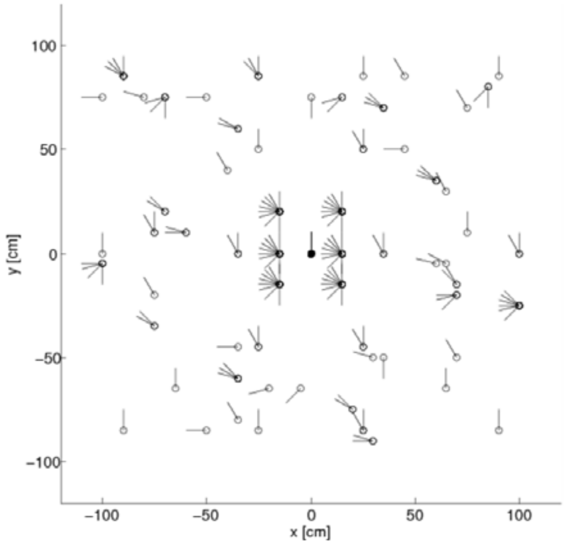

Fig. 5: subset of the 150 oriented targets for 9 distinct orientations used for the experiment

5. Experimental Setup

One key requirement for our study of stepping was that subjects should not search for the target. For this reason we have inverted the experimental setup compared to prior studies: in our case the target is always at the same position and orientation in the room (Fig 6.). The experimenter has to indicate the randomized starting location relatively to this constant spatial reference. This is done by projecting a thick line in a calibrated 3x3m^2 area (Fig. 8). Once the subject was positioned symmetrical along this line the operator was giving a start signal and the subject was recorded until the fixed target was reached (Fig. 7).

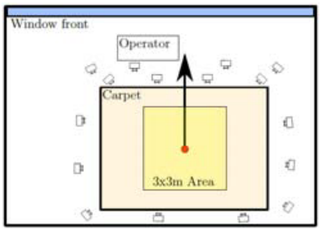

Fig. 6: fixed target location (red point) with target orientation facing the window side.

Fig. 7: video-projected line indicating the start position and orientation (left) and target position with implicit target orientation (right).

Five male subjects participated to the measurements (age 21.6 +/- 1.8, height 1.79 +/- 0.04m) and were paid for the two spent hours. The motion capture was minimally invasive as they could keep their personal clothes. They only had to wear light shoes to ease the feet capture (Fig 7.).

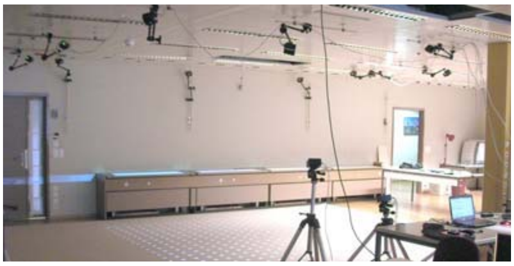

Fig. 8: calibrating the experimental area

6. Results

The captured marker positions were filtered with a 3^{rd} order Butterworth filter with a cutoff frequency of 5Hz. Then we ran a step filtering stage [2] to discard "false steps" that were sometimes performed at the very end of the movement when a subject was simply changing his foot of support with negligible change in the foot location.

For each oriented target, the measured numbers of steps were combined by retaining the most frequent number (mode) of steps. In case two results had equal frequency, the lower one was chosen. Figure 9 shows side to side the comparison of the predicted (left) and the measured (right) modes for four target orientations. Each cell contains only one target and is colored with the same color coding as in Fig 3.

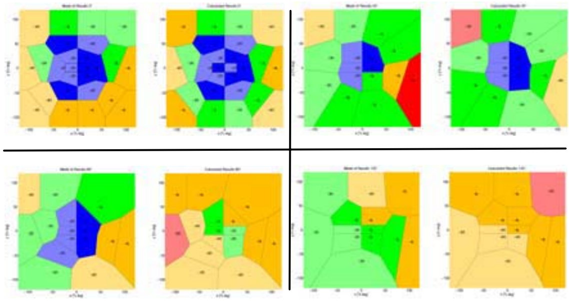

Fig. 9: predicted and measured step modes for for 0° (top left), 45° (top right), 90° (bottom left) and 135° (bottom right)

7. Discussion and Future Work

On Fig. 9 top left corner (0°), we can see that the predictions (left) match the measurements for the frontal region but tend to predict less steps for target behind the subject. It seems that the subjects tend to turn a lot in the first step to get the target in their field of view first but this should be confirmed by a deeper analysis of the data. For the other target orientations, the model tends to predict more steps than the real subjects would use. One possible explanation is that the cost of performing a turn is too high in the optimization.

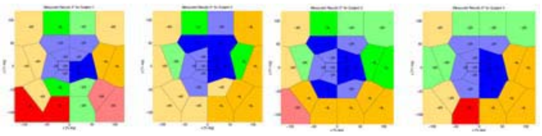

Fig. 10: variability among 4 subjects for 0°

Another key observation is the high variability among subjects (Fig. 10). This can be explained by the large range of solutions to reach a goal, so some subject would tend to prefer one strategy over another (e.g. if the goal is strictly behind the subject, one could step backward in straight line or turn on either side).

We believe the proposed fixed target concept associated with the video projected start location to be efficient tools for future larger scale measurement campaigns. In particular we intend to record trajectories with a denser target sampling and more subjects. Stepping is clearly a more complex motion pattern than locomotion in terms of coordination of balance and displacement. It is also more likely to induce subject specific comfort strategies as it is more constrained by anatomical joint limits than locomotion. Finally, the hypothesis whether the target visibility determines the start strategy needs to be confirmed.

8. Acknowledgements

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