Gait & Posture 37 (2013) 385–390

Contents lists available at SciVerse ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Strategies of locomotor collision avoidance

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ARTICLE INFO

Article history:
Received 20 July 2011
Received in revised form 12 June 2012
Accepted 7 August 2012

Keywords:
Navigation
Locomotion
Human
Motor control

ABSTRACT

Collision avoidance during locomotion can be achieved by a variety of strategies. While in some situations only a single trajectory will successfully avoid impact, in many cases several different strategies are possible. Locomotor experiments in the presence of static boundary conditions have suggested that the choice of an appropriate trajectory is based on a maximum-smoothness strategy. Here we analyzed locomotor trajectories of subjects avoiding collision with another human crossing their path orthogonally. In such a case, changing walking direction while keeping speed or keeping walking direction while changing speed would be two extremes of solving the problem. Our participants clearly favored changing their walking speed while keeping the path on a straight line between start and goal. To interpret this result, we calculated the costs of the chosen trajectories in terms of a smoothness–maximization criterion and simulated the trajectories with a computational model. Data analysis together with model simulation showed that the experimentally chosen trajectory to avoid collision with a moving human is not the optimally smooth solution. However, even though the trajectory is not globally smooth, it was still locally smooth. Modeling further confirmed that, in presence of the moving human, there is always a trajectory that would be smoother but would deviate from the straight line. We therefore conclude that the maximum smoothness strategy previously suggested for static environments no longer holds for locomotor path planning and execution in dynamically changing environments such as the one tested here.

1. Introduction

On our way back from work, we cross path with dozens, maybe even hundreds of people, but hardly ever we experience a collision with someone else. Our ability to infer the others' intentions from action observation (for review, see [1]) apparently enables us to rapidly recognize others as being potential obstacles and predict their future path. Consequently we are able to adapt our own motion in order to avoid collisions. However, there are infinitely many possible solutions to avoid collision with a moving obstacle [2]. The analysis of whole body motion in the presence of static obstacles (e.g., [3,4]) or boundary conditions has shown that walking trajectories, just like arm movements, are stereotypical under the repeated conditions [5,6]. This suggests that humans use a specific strategy to solve the problem of trajectory formation for goal-directed locomotion, i.e., walking from one location to another. Previous studies have proposed that humans minimize a cost associated with a trajectory and that this minimization is equivalent to a maximum-smoothness strategy [7,8].

Whether this strategy also holds for collision avoidance is yet unknown and investigations in the presence of moving obstacles are relatively rare [9–12]. Whereas some studies have analyzed how visual information affects perception of the others' movement [3,13] and of obstacles [14,15], other investigations on human locomotion behavior focused on average behavior of crowds (e.g., [16–18]). For human-aware robot control, which also faces the problem of obstacle avoidance (e.g., [19]), a common strategy, often based on the concept of 'proxemics' [20], has been adopted for different cases of obstacle avoidance and types of interactions [21]. While static obstacles can easily be circumvented by a global path planning procedure, the exact trajectory of moving obstacles cannot be predicted without error and thus may require local planning, i.e., feedback about the current location or motion of the obstacle has to be incorporated to initiate re-planning and corrections.

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http://dx.doi.org/10.1016/j.gaitpost.2012.08.003

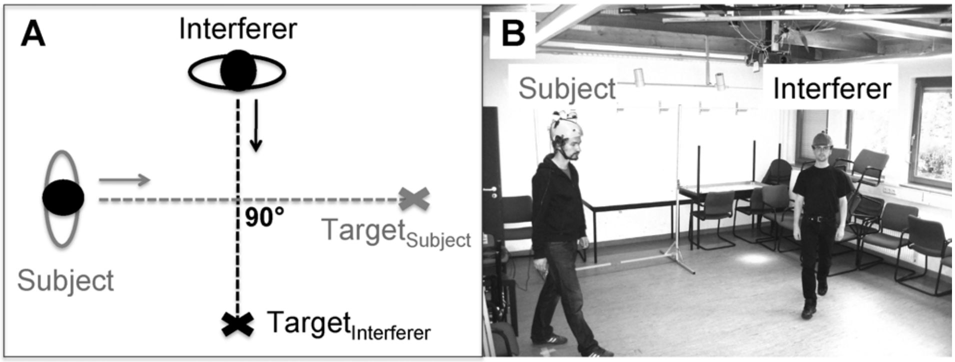

Fig. 1. Experimental setup. Subject and interferer were instructed to reach a pre-defined target position. At an acoustic signal, both participants started to walk from initial positions at an equal distance to the intersection point of their paths. The interferer was instructed to pass before the subject and avoid gaze contact. (A) Overhead view of the experimental setup. (B) Experimental situation.

In the current work, we first asked whether collision avoidance in the presence of another moving agent results in stereotypical trajectories, which would suggest a predefined strategy. We then analyzed collision avoidance under different conditions in order to clarify whether minimization of smoothness costs adequately describes the experimental findings. In order to disentangle different possibilities of trajectory formation, we devised a simple model using a maximum-smoothness constraint [22,23] and simulated our experimental conditions.

2. Materials and methods

2.1. Experiments

13 subjects (age 25–43, height 165–193 cm, 7 females) participated in the experiments. Two persons, an interferer (male, 37 years old, height 179 cm) and one subject walked from a predefined starting position to a fixed goal position marked on the floor (distance 4 m). The starting angle between the two intended paths was 90° and the starting positions were at the same distance from the intersection (Fig. 1A). Using a motion tracking system (IS-600 Mark 2, InterSense Inc., USA), the head position of the subject was tracked using a 6-DOF sensor mounted on a helmet (Fig. 1B) using infrared and ultrasound signals at 150 Hz and the head position of the interferer was tracked with a wireless sensor at 20–50 Hz. The size of the tracked area was 4 m × 4 m in the middle of a room of 38 m^2. All experiments were done with open eyes and natural lighting conditions. The interferer and the subjects were instructed before the experiment about their task (see below) and told not to communicate verbally. Subjects were told to walk at their preferred, natural pace and gave their written consent prior to the experiment according to the Declaration of Helsinki.

Four different conditions were tested for each subject in 11 consecutive trials: (*1: None*) subject walked alone from the start to the end position without obstacle (4 trials); (*2: Moving*) subject and interferer started to walk at a common starting signal (4 consecutive trials); (*3: Catch*) subject and interferer walked simultaneously but the interferer stopped unexpectedly at the intersection with the subject's path (one trial per subject); (*4: Retest*) scenario (2) was repeated twice. In the *Moving* obstacle condition, the interferer was instructed not to consider the behavior of or look at the subject, but to try being the first to pass. The subject was informed that the interferer would not react to the subject. Condition (3), the catch trial, was used to assess on-line correction strategies when an unexpected event/obstacle occurs. In condition (4) the scenario presented in (2) was repeated to test whether the previous catch trial influenced the behavior of the subject.

2.2. Data analysis

Raw data were analyzed using Matlab (The Mathworks, Natick, MA). 3D position data were filtered using a Gaussian low pass filter (cutoff frequency 2 Hz). The resulting trajectory was differentiated to yield 3D velocity. To define start and end of a movement, a velocity criterion of 20% of the maximum speed was used. Velocity profiles were normalized before averaging. Smoothness of the trajectory is quantified by the integrated squared jerk and the cost J is computed as follows [22]:

$$J = \int_0^{t_E} \dddot{x}(t)^2 + \dddot{y}(t)^2 dt$$

where (x,y) are the Cartesian coordinates of the subject position and t_E is the movement duration. Minimizing higher derivatives than jerk (e.g., snap, crackle, or pop) would be possible [7], but would lead to sharper velocity peaks than found experimentally [23]. Statistical analysis was performed using the Statistics Toolbox of Matlab. The significance level was set to a p-value of 0.05.

2.3. Simulation of human walking behavior

We simulated the subject's trajectory by minimizing the jerk of the movement in the presence of a pre-defined interferer. Minimum jerk motion was computed given the velocity and position at the two endpoints using the algorithm presented in [24] and the respective Matlab script *min_jerk.m.*[1] In addition to endpoint constraints, we defined one via-point on the path to account for the path planning. Time of passage, position, and velocity at the via-point were obtained from the experimental velocity profiles. Thus, the simulated movement profile was the minimum jerk movement given the particular via- and endpoint constraints, which are described in Section 3. The overall walking duration was set to 4 s. Simulations were performed using the Matlab software (The Mathworks, Natick, MA).

3. Results

3.1. Experiments

In general, trajectories were very stereotyped both within and between subjects demonstrating that the same strategy was used

[1] http://www.cs.washington.edu/homes/todorov/software/min_jerk.m.