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Linking pedestrian flow characteristics with stepping locomotion

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HIGHLIGHTS

- The relations between transport characteristics of pedestrian dynamics like speed or density and properties of human locomotion like step length and frequency are investigated and evaluated.
- The effect of physical properties of human body on characteristics of human locomotion changes with density. The influence of individual properties like body height decreases with the degree of congestion.
- Different types of step adaptation under congested conditions are observed and studied.

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ABSTRACT

While properties of human traffic flow are described by speed, density and flow, the locomotion of pedestrian is based on steps. To relate characteristics of human locomotor system with properties of human traffic flow, this paper aims to connect gait characteristics like step length, step frequency, swaying amplitude and synchronization with speed and density and thus to build a ground for advanced pedestrian models. For this aim, observational and experimental study on the single-file movement of pedestrians at different densities is conducted. Methods to measure step length, step frequency, swaying amplitude and step synchronization are proposed by means of trajectories of the head. Mathematical models for the relations of step length or frequency and speed are evaluated. The problem how step length and step duration are influenced by factors like body height and density is investigated. It is shown that the effect of body height on step length and step duration changes with density. Furthermore, two different types of step in-phase synchronization between two successive pedestrians are observed and the influence of step synchronization on step length is examined.

1. Introduction

The fundamental diagram, the relation between speed, flow and density, describes the transport properties of pedestrian streams and thus allows to determine the capacity of pedestrian facility or to forecast the condition for the occurrence of

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congestion. A lot of researches on the fundamental diagram have been conducted [1–19]. However the fundamental diagrams reported in the literature differ significantly [20]. Beside methodological problems in the measurement of the relation [21], psychological factors like emotion, perception or cognition, sociocultural factors like cultural background, groups or gender as well as physical properties of a pedestrian like the body height or weight are potential causes for this diversity. Relating gait characteristics given by the locomotor system and physical properties of human body with transport characteristics like speed and density [6,21–28] could be an approach to reduce the complexity. In the next paragraphs we summarize studies focusing on the relation outlined above.

The measurement of step length and swaying amplitude is helpful to estimate pedestrians' required space under walking conditions [6,29], which is one criterion determining the level of service and thus a factor for facility design. The influence of step adaptation on the decrease of speed with density was discussed by von Sivers et al. [28] and Seyfried et al. [6,21,26]. Adjusting step length and frequency to the limited space by rhythm could increase the flow in a congested situation, which can be applied to guiding and controlling pedestrian flow [30]. Moreover, taking a deeper look at how people do their steps is important for investigating some phenomena in human traffic flow, like the zipper effect [29,31–35] and the step-and-slide movement [27,29,36]. For pedestrian safety, reducing the risk of falls and disasters, full knowledge of stepping locomotion both on the plane and on stairs is required [37,38].

Till now only few studies on stepping locomotion have been conducted. They focus on step length, frequency, swaying amplitude and step synchronization. For the relationship between step length (frequency) and speed of pedestrians under free-flow condition, linear functions are proposed [39–43]. However, the parameters estimated for the linear functions are different. Jelić et al. [44] studied the relation of pedestrians with longitudinal interaction and found a linear relationship as well. Also a piecewise linear function was proposed to describe the relation [25]. Non-linear relations were suggested by Dean [22], Inman et al. [23] and Hoogendoorn et al. [29]. Grieve and Gear [45] found that the age influenced whether the relationship was linear or non-linear. The discussion above shows that the relations between step length (frequency) and speed proposed by different researchers do not agree. The relation between the swaying amplitude and speed was mentioned by Inman et al. [23], Hoogendoorn and Daamen [29] and Liu et al. [46]. The phenomenon of lock-steps or step synchronization optimizing the utilization of the available space has been observed at high as well as low densities [44] . The influence of synchronicity and anti-synchronicity of steps was analyzed in Ref. [47]. Navin et al. [48] observed that the highest flow occurred on the narrow sidewalk as in the case of disciplined marching formation. Besides, step synchronization was a possible explanation for the fact that the linearity between the required length and the velocity [6]. Although step synchronization plays a critical role, its influence on human traffic flow has not been investigated in detail up to now.

State-of-the-art models for human traffic flow represent pedestrians as points or circular or elliptic areas. But human motion bases on steps determining the maximal speed, abilities of turning and many more. To match human motion more closely, stepping locomotion is taken into account by models for human traffic flow. Since the step length affects the size of the ellipses that govern the repulsive effects in the Social Forces model [49], the exploration of stepping locomotion and its affecting factors is necessary [27]. In the adaptive velocity model, the relationship between step length and speed is one of inputs to define pedestrians' velocities for different states including deceleration, acceleration and collision [26]. Inspired by this model, Chraibi et al. [50] extended it to two dimensions by introducing ellipses as the projection of required space of the human body on the plane. Considering step length and lateral swaying of body, the length of the ellipses increased with speed while the width decreased with the speed. The relation between step length and headway was adopted to guide the movement of pedestrians in a continuous distance model (CDM) [51]. Considering the pedestrians' stepwise movement, the Optimal Steps Model was derived from cellular automata to reproduce the natural grid-free trajectories [41,42,52]. In this model, the space available for the next step of a pedestrian was determined according to the relation between step length and speed. This model was further developed by replacing the former optimization on a circle around the pedestrian with optimization on the full disc [28]. In Ref. [53], the space around a pedestrian consisted of two parts. One was the step length and the other was given by physiological constraint. Via the non-linear relation between step length and speed, the required space to move at a particular speed and the natural speed for a given available space was obtained. This natural speed was used to modify the preferred speed of the agent in this model. Concerning the single-file pedestrian movement with lock-step effect, a new estimating-correction cellular automation ECCA was proposed [54]. To simulate pedestrian movement in different pedestrian facilities like stairs where the depth of a step of the stair limits the step length, the correlation between step length, step frequency and speed was adopted [55]. Compared with plane, the effect of density on the flow on stairs was small [55] and step frequency may be a dominant factor to decide the walking speed [56].

In conclusion, study on human stepping locomotion is not only essential for human traffic flow theories and model development, but also important for pedestrian facility design, the organization of mass events, the prevention of crowd disaster and emergency evacuation. Therefore, the stepping locomotion and step adaptation including step length, step frequency, swaying amplitude and step synchronization are studied in this paper. The characteristics of these variables are analyzed. The structure of the paper is as follows: Section 2 describes the experiment setup and data preparation. Section 3 introduces the methods for the measurement of step length, step duration (step frequency) as well as swaying amplitude, and the calculation of the stepping phase. Section 4 shows the results and discussions including the relationship between step length (step frequency) and speed, the dependency of swaying amplitude on speed, the interdependency among step length, density and body height, the identification of step synchronization and its influence on the step length. The conclusion and outlook is presented in Section 5. An Appendix presents some detailed information for the relation between swaying amplitude and speed.