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A portable system for foot biomechanical analysis during gait

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ABSTRACT

Modeling the foot is challenging due to its complex structure compared to most other body segments. To analyze the biomechanics of the foot, portable devices have been designed to allow measurement of temporal, spatial, and pedobarographic parameters. The goal of this study was to design and evaluate a portable system for kinematic and dynamic analysis of the foot during gait. This device consisted of a force plate synchronized with four cameras and integrated into a walkway. The complete system can be packaged for transportation. First, the measurement system was assessed using reference objects to evaluate accuracy and precision. Second, nine healthy participants were assessed during gait trials using both the portable and Vicon systems (coupled with a force plate). The ankle and metatarsophalangeal (MP) joint angles and moments were computed, as well as the ground reaction force (GRF). The intra- and inter-subject variability was analyzed for both systems, as well as the inter-system variation. The accuracy and precision were, respectively 0.4 mm and 0.4 mm for linear values and 0.5° and 0.6° for angular values. The variability of the portable and Vicon systems were similar (i.e., the inter-system variability never exceeded 2.1°, 0.081 N m kg^{-1} and 0.267 N kg^{-1} for the angles, moments and GRF, respectively). The inter-system differences were less than the inter-subject variability and similar to the intra-subject variability. Consequently, the portable system was considered satisfactory for biomechanical analysis of the foot, outside of a motion analysis laboratory.

1. Introduction

Currently, 3D biomechanical analysis of the foot is commonly used for clinical evaluation. This tends to include description of motion of various anatomical segments of the foot. Approximately fifteen models have been developed and proposed in the literature [1], including the Milwaukee foot model [2,3], the Oxford foot model for adults [4,5] and children [6,7] and the Heidelberg foot measurement method [8]. Spatial coordinates of anatomical landmarks are used to calculate the kinematic and dynamic parameters. Several methods have been used for these purposes, based either on skin markers [1–8] or intracortical bone pins with markers [9–11]. Irrespective of the foot model or the method, a motion capture system and a force plate are required to perform the kinematic and dynamic analysis.

To analyze the temporal, spatial, or pedobarographic parameters, some portable systems (e.g., GAITRite®, Footscan®) with pressure-activated sensors have been devised. To the best of our knowledge, a portable system to analyze foot kinematics and dynamics during gait has not yet been presented. This system could help measure foot biomechanics in patients, bringing the measurement system to the patient rather than forcing the patient to come to a purpose-built laboratory. The goal of this study was to design and evaluate a portable system for the kinematic and dynamic analysis of the foot during gait.

2. Methods

2.1. Description of the portable system

The system consisted of four blocks (dimensions of 80 cm, 60 cm and 6 cm for the length, width and height, respectively) that were assembled to create a 3.2 m walkway (Fig. 1a). A force plate (1000 Hz, Kistler, Kistler Instruments, Winterthur, Switzerland) was integrated into one of the walkway blocks to record the ground reaction force and moment exerted by the foot during gait. The force plate was independent of the walkway (i.e., a 2 mm space was between the force plate borders and the

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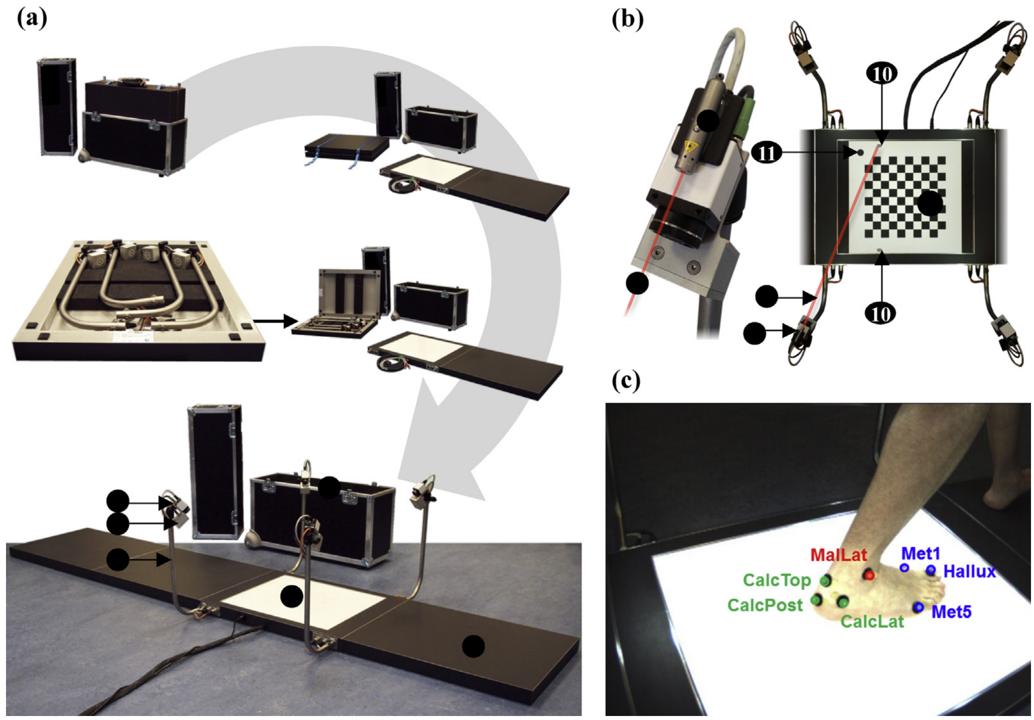

Fig. 1. (a) Assembly of the portable system from the storage box to complete installation. The camera system was stored in a walkway block (1, storage box; 2, main walkway block with an integrated force plate; 3, walkway block; 4, support arm; 5, camera; 6, LED lamp); (b) Checkerboard for camera calibration and laser for camera setting (7, checkerboard; 8, red laser; 9, laser ray; 10, reference points to set camera in the right direction; 11, reference point to position the checkerboard in the right direction); (c) Pictures from the MSC software to illustrate color marker detection.

walkway frame) and was only fixed to the walkway block by footplates. Four metallic arms were fixed on each corner of the walkway block containing the force plate. A lamp (9 LEDs) and a camera (140 Hz, 656 × 490 pixels) were fixed to each of these arms with a ball joint to enable camera orientation. The measurements described below (Sections 2.2 and 2.3) were recorded at 100 Hz. The complete camera system (i.e., arm, lamp and camera) can be stored inside the walkway block. The ethernet connection and power supply of the camera system were integrated in the walkway block containing the force plate. The complete system is transportable in a storage box (84 cm, 28 cm and 70 cm, for the length, width and height, respectively). Additional technical information is given in Appendix 1.

Software for sensor synchronization (MSC, Multi Sensor Control, Lion Systems S.A., Foetz, Luxembourg) was used to record simultaneously data from the cameras and force plate. A system calibration was performed by placing a checkerboard on the top of the force plate (Fig. 1b). The cameras were positioned using a laser placed on top of each camera and a 'reference point' on the checkerboard. The system recorded the 3D coordinates of colored markers located on the foot and leg (Fig. 1c) (Appendix 2).

2.2. Accuracy and precision of the measurement system

To evaluate accuracy and precision, measurements were first performed on defined reference objects. Three phantoms of different lengths representing three different foot sizes (13, 18 and 26 cm corresponding approximately to the feet of a one-year-old child, a 6-year-old child and an adult woman, respectively) were constructed from Lego® bricks (Fig. 2a). Proportions of the

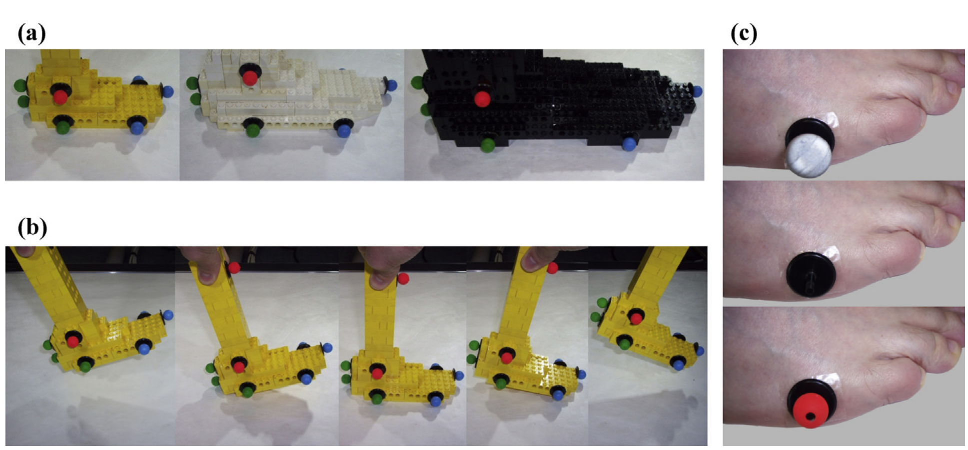

Fig. 2. (a) Phantom feet (from left to right: feet 1–3); (b) Simulation of a foot rollover; (c) Color and reflective markers with the same base location.