TITLE:

Lower Limb Biomechanical Analysis of Healthy Participants

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SUMMARY:
This article introduces a comprehensive experimental methodology on two of the latest technologies available to measure lower limb biomechanics of individuals.

ABSTRACT:
Biomechanical analysis techniques are useful in the study of human movement. The aim of this study was to introduce a technique for the lower limb biomechanical assessment in healthy participants using commercially available systems. Separate protocols were introduced for the gait analysis and muscle strength testing systems. To ensure maximum accuracy for gait assessment, attention should be given to the marker placements and self-paced treadmill acclimatization time. Similarly, participant positioning, a practice trial, and verbal encouragement are three critical stages in muscle strength testing. The current evidence suggests that the methodology outlined in this article may be effective for the assessment of lower limb biomechanics.

INTRODUCTION:
The discipline of biomechanics primarily involves the study of stress, strain, loads and motion of biological systems - solid and fluid alike. It also involves the modelling of mechanical effects on the structure, size, shape and movement of the body[1]. For many years, developments in this field have improved our understanding of normal and pathologic gait, mechanics of neuromuscular control, and mechanics of growth and form[2].

The main objective of this article is to present a comprehensive methodology on two of the latest technologies available to measure lower limb biomechanics of individuals. The gait analysis system measures and quantifies gait biomechanics by using a self-paced (SP) treadmill in combination with an augmented reality environment, which integrates a SP algorithm to regulate the treadmill's speed, as described by Sloot et al[3]. The muscle strength testing equipment is used as an assessment and a treatment tool for upper extremity rehabilitation[4]. This device can objectively assess a variety of physiological patterns of movement or job simulation tasks in isometric and isotonic modes. It is currently recognized as the gold standard for upper limb strength measurement[5] but the evidence related specifically to the lower limb remains unclear. This paper explains the detailed protocol for completing an assessment of gait and isometric strength for the lower extremity.

Within biomechanical analysis, it is useful to combine assessments of functional performance (such as gait analysis) with specific tests of muscular performance. This is because whilst it may be assumed that increased muscle strength improves functional performance, this may not always be apparent[6]. This understanding is required for the improved future design of rehabilitation protocols and research strategies to assess these approaches.

PROTOCOL:

The method reported was followed in a study that received ethical approval from the Bournemouth University Research Ethics Committee (Reference 15005).

1. Participants

1.1. Recruit healthy adults (aged from 23 to 63 years, mean ± sd; 42.0 ± 13.4, body mass 70.4 ± 15.3 kg, height 175.5 ± 9.8 cm; 15 males, 15 females) to participate in the study. Thirty participants were recruited for this study.

1.2. Ensure that there is no self-reported history of dizziness, balance problems or walking difficulties in the participants.

1.3. Ensure that participants did not suffer from any known neuromuscular injury or condition affecting balance or walking.

2. Setup and procedures for gait analysis

2.1. Use a gait analysis system (**Figure 1**) comprising of a dual-belt force plate-instrumented treadmill, a 10-camera motion capture system and a virtual environment that provides optic flow.

2.2. Ensure participant is wearing very tight non-reflective clothing such as cycling shorts or leggings.

2.3. Using double sided adhesive tapes attach 25 passive reflective markers and place according to the lower body configuration of the Human Body Model (HBM) [7] as detailed in **Table 1** and **Figure 2**. [The information in this document is taken from the Motek 'HBM Reference Manual[8]]

2.4. Use a joint ruler to take measurements of the required knee and ankle widths for the HBM[6].

2.5. Secure participant to a safety harness which is fastened to an overhead frame.

2.6. Start a new session in the database and make sure it is active (highlighted).

2.7. Using the subject tab, create a new participant from a 'Labelling Skeleton' button.

2.8. Browse to the 'LowerLimb HBM_N2.vst' file and then enter the name of the participant. The new participant appears in the Subjects pane.

2.9. Go to the Tools pane and open the 'Subject Preparation' tab.

2.10. 'Zero level' the forceplates via the 'Hardware' tab. (Make sure no weight is exerted on the force plates).

2.11. Prepare the participant for the ROM trial by having them ready in the middle of the treadmill.

2.12. To ensure the participant can accustom themselves to the self-paced treadmill, ask them to walk at a comfortable speed for 5 mins at the beginning of the session[9,10].

2.13. Following the acclimatization, without any delay time ask the participant to walk for a minimum of 5 min[10,11].

2.14. Ensure participants are blinded to the timing of the recordings.

2.15. Ensure treadmill and start data recordings by clicking the 'Start recording' button[12]. This can be done with integrated software [please see **Table of Materials**].

2.16. Stop the recording after acquiring the desired amount of data. It is recommended to collect three sets of 25 cycles.

2.17. Open the processing software [please see **Table of Materials**] and remove the high-frequency noise on data, by selecting a low-pass filter to the marker data such as a second order Butterworth filter with a cut-off frequency of 6 Hz.

2.18. Go to 'File', and then select 'Export' to save as '.CSV' format.

2.19. Determine individual strides from vertical force data and use the foot markers to ascertain gait events[13].

2.20. Analyze the gait parameters such as kinematic, kinetic and spatial-temporal data in Matlab R2017a [please see **Supplementary File**].

3. Setup and procedures for muscle strength test

3.1. Use the muscle strength testing equipment (multimodal dynamometer) (**Figure 3**), to measure participants' muscle strength based on Maximum Voluntary Isometric Contraction (MVIC) [14].

3.2. Attach the tool/pad number 701 to the dynamometer exercise head.

3.3. Test participant's right and left knee isometric muscle strength.

3.4. Test participants in a seated position on a chair with a backrest.

3.5. Using the up/down switch, align the dynamometer axis with the knee joint's anatomical axis of rotation. Place the pad of the tool centrally at the lower part of the shin of the tibia.

3.6. Keep the knee at 90° flexion, the hip in neutral rotation and abduction, and the foot in plantar flexion.

3.7. Place the participant's hands on their abdomen and stabilize the trunk, hips, and mid-thigh on the chair with Velcro straps.

3.8. Run a practice trial for participants to get accustomed to the testing manoeuvre.

3.9. Instruct the participant to extend their knee (exert pressure upwards on the pad) followed by flex (exert pressure downwards on the pad) to exert a maximum contraction on the command "Go" for 3 s.

3.10. Provide verbal prompts and encouragement ("Push" for upwards and "Pull" for downwards) during the strength testing.

3.11. Ensure that participants are aware they can stop the test immediately if they experience any unusual pain or discomfort.

3.12. Allow participants to rest for 2 mins.

3.13. Repeat steps 3.1 – 3.12, three times for left and right leg and record the data in newtons (N).

3.14. Save all the data and export as a report for the analysis.

REPRESENTATIVE RESULTS:

The mean and standard deviation of the spatial-temporal, kinematics, and kinetic gait parameters are given in **Table 2**. MVIC data for all 30 participants are summarized in **Table 3**. A typical set of data for one participant showing graphical representation of gait parameters is provided in **Figure 4**.

The data presented are representative of the results obtained across all participants, and are consistent with textbook reference results obtained for gait and isometric strength testing[15].

FIGURE AND TABLE LEGENDS:

Figure 1: Gait analysis system. The GRAIL system is used to measure gait parameters. This system consists of a split-belt instrumented treadmill, 160° semi-cylindrical projection screen, force sensors, video cameras and optical infrared system.

Figure 2: Diagram of markers used in Human Body Model (HBM). This figure shows the exact placements of all markers in the HBM lower body model. Special attention should be paid to the placement of the markers printed in green (bold in Table 1); these are used during initialization to define the biomechanical skeleton.

Figure 3: The muscle strength testing equipment (multimodal dynamometer) used to measure participants lower limb muscle strength. This system is used to measure participants' muscle strength based on Maximum Voluntary Isometric Contraction (MVIC).

Figure 4: A sample report produced from offline analysis of the gait assessment using the proposed technique. Spatial temporal data and kinematic and kinetic gait cycle for one participant.

Table 1: Markers used in the Human Body Model (HBM). This table shows the exact placements of all markers in the HBM lower body model. Special attention should be paid to the placement of the markers written in bold; these are used during initialization to define the biomechanical skeleton.

Table 2: The mean and standard deviation of the spatial-temporal, kinematics, kinetic gait parameters for the 30 participants. Gait parameters are reported for the left and the right side separately.

Table 3: The mean and standard deviation of the Maximum Voluntary Isometric Contraction (MVIC) for knee joint using the muscle strength testing equipment for the 30 participants.

DISCUSSION:

The contribution of this study is to accurately and comprehensively describe within one protocol the techniques for combined gait analysis and muscle strength testing that have not previously been described together.

In order to achieve accurate results for gait analysis, there are two areas that require maximum attention: 1) marker placements and 2) acclimatization time. The accuracy of the measured data is heavily dependent on the accuracy of the model used. The other key factors that affect accuracy include erroneous marker movement due to superficial skin deformation relative to the underlying skeletal structure, and the resolution of the tracking system[16]. **Figure 2** shows the exact placements of all markers in the HBM lower body model. Special attention should be given to the placement of the markers printed in green; these are used during initialization to define the biomechanical skeleton. Participants were asked to walk for at least 5-minutes to adapt to SP treadmill walking[17,18]. The SP mode was chosen in order to allow participants a more natural stride variability[3]. However, studies have shown that walking speed varies more during SP walking and gait disturbance could occur through acceleration or deceleration of the belt[3]. In line with other studies[13,19], to minimize this effect, we recommend at least five minutes[19] should be allowed for acclimatization.

To measure participants' muscle strength using the muscle test equipment there are three critical stages: 1) alignment of knee joint with the dynamometer axis, 2) practice trial, and 3) verbal encouragement. Inappropriate alignment between the dynamometer and knee joint axis of rotation can introduce a factor confounding accurate isometric assessment[20]. Throughout the study, all participants were given precise instruction about the system prior to taking part. However, a practice trial and verbal encouragement are two factors which can greatly affect the MVIC[14]. Many of the individuals who underwent the strength test have very limited or no experience in performing strength testing manoeuvres. Strength testing has generally been shown to be reliable[21], but it has been shown that strength scores of novice participants are likely to improve on subsequent testing as they become more comfortable and familiar with the test and the system[22]. Verbal encouragement during exercise testing has been shown to enhance maximal force[23], rate of force development[23], muscle activation[24], muscular endurance[25], power[26], maximal oxygen consumption[27], and time to exhaustion[27,28]. Therefore, we highly recommend adopting this step.

Overall, the data presented here are representative of textbook reference results for gait and isometric strength testing obtained on other equipment. Therefore, it is proposed that the methodology outlined in this article may be considered effective in the assessment of gait and muscular strength in healthy individuals. Further studies should evaluate the reliability of these systems before they are used in clinical applications.

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The authors have nothing to disclose.

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