Title: Computer-vision aided functional movement measurement in people with and without axial spondyloarthritis – validation and feasibility study protocol

Authors: Erin Hannink PhD, DPT[1], Maedeh Mansoubi, PhD[2], Neil Cronin, PhD[3,4], Benjamin Waller, PhD[3], Helen Dawes, PhD[1,2,5]

Affiliations: 1. Centre for Movement, Occupational and Rehabilitation Science (MOReS), Oxford Brookes University; 2. College of Medicine and Health, University of Exeter; 3. Neuromuscular Research Centre, Faculty of Sport and Health Sciences, University of Jyvaskyla, Finland; 4. School of Sport and Exercise, University of Gloucestershire, UK; 5. Oxford Health, Biomedical Research Centre, University of Oxford

Declaration of Interests
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Abstract
Back pain is a common form of disability worldwide, and one condition that causes chronic back pain is axial spondyloarthritis (axSpA) which primarily affects spinal joints resulting in pain and joint stiffness. There have been several tools developed to assess joint mobility for the axSpA population, but each requires either a clinician for measurement or specialised equipment. Markerless human motion analysis uses a computer-vision (CV) aided system to automate human movement from videos. This study aims to estimate criterion validity and reliability of functional movement measurement using a CV-aided system by comparing it to a standard clinical measurement; secondarily, to assess the feasibility of the CV-aided system in the lab and home environments. An index of tests of functional movement, range of motion and posture will be captured on video and measured using the CV-aided system in the lab and home environments. The index of tests will be compared to measurement performed by an experienced physiotherapist. Bland-Altman plots will be used to determine agreement between the methods, and reliability and completion rates will be used to determine the feasibility of the CV-aided system.

Keywords: Computer vision, validity, functional movement, chronic back pain

Background

Back pain is the most common form of disability worldwide[1]. In the UK, an estimated one-third of adults are affected each year[2]. Back pain accounts for 20% of all musculoskeletal consultations, costing the NHS £1bn annually, and lost productivity and sick leave costs the UK economy an estimated £20bn a year[3]. One condition that causes chronic back pain is axial spondyloarthritis (axSpA), a long-term inflammatory arthritic condition that primarily affects spinal joints and results in chronic back pain and joint stiffness and loss of range of motion[4]. AxSpA, which includes both nonradiographic axSpA and ankylosing spondylitis (AS), affects more than 220,000 people in the UK, which is approximately 5 in 1,000 adults[5]. Symptoms of axSpA first present as 'normal' back pain in people between 20-30 years old and it is often misdiagnosed or diagnosis is delayed; full diagnosis can take an average of 8.5 years[6]. This delay has high-cost implications and negatively impacts the treatment of this life-long condition[6].

There have been several tools developed to assess joint mobility in the axSpA population. The most common non-radiographic clinical assessment tool is the Bath AS Metrology Index (BASMI), an index of five simple clinical measurements to assess the axial status[7]. The Edmonton Ankylosing Spondylitis Metrology Index (EDASMI) is a similar index of four clinical measurements that was developed to be more responsive to change than the BASMI[8]. In an effort to increase measurement precision of the BASMI and EDASMI which are both tools measured by clinicians, the University of Cordoba Ankylosing Spondylitis Metrology Index (UCOASMI) was developed[9]. The UCOASMI is an index of tests measured by automated motion capture using four cameras and 33 reflective markers placed on anatomical landmarks[9,10]. Even more recently, inertial measurement unit (IMU) sensor based systems have been used to measure spinal mobility in the axSpA population using five IMUs mounted along the spine to measure spinal mobility[11,12].

All of these tools and methods require either a clinician for measurement or specialised equipment (motion capture system or IMUs), thus not providing means for accurate and precise remote measurement which could empower self-management of long-term conditions like axSpA. Markerless human motion analysis has been developed and is evolving to enhance telerehabilitation[13]. This kind of system uses algorithms from computer-vision (CV) aided system which is a branch of artificial intelligence to automate the analysis of human movement from videos. CV-aided methods could be used to analyse specific functional movements captured on video thereby helping both clinicians and patients and bridging the gap between the clinic and

home. This is especially critical in a long-term condition, such as axSpA, which typically has symptoms of both pain and reduced range of motion and flexibility.

Following COSMIN (COnsensus-based Standards for the selection of health Measurement INstruments) guidelines[14] and the SPIRIT (Standard Protocol Items: Recommendations for Interventional Trials) statement[15], this study is aiming to estimate criterion validity and reliability of functional movement measurement using a CV-aided system (CVAS) by comparing it to a standard clinical measurement performed by an experienced physiotherapist. Secondarily, it aims to assess the feasibility of the CVAS in the lab and home environments in terms of the reliability and completion rates.

Methods/Design

Study design

This study is designed to achieve both the measurement property and feasibility aims. The first part will involve measurement of the CVAS in a movement laboratory setting with reference testing by an experienced physiotherapist. The second part will involve measurement of the CVAS in a home environment.

Participants

Men and women aged 18 years or older who are able to provide informed consent for participation and who are willing and capable of uploading videos from a smartphone or webcam will be included in the study. People with and without chronic back pain will be included for comparison in the study. Participants will be included for the group with back pain if they are diagnosed with axSpA or have chronic non-specific low back pain (LBP). For the healthy volunteer group, participants will be included if they have no long-standing back pain. People will be excluded from participation if any of the following apply: has had surgery within six months, unable to stand independently, unable to pass screening questions to participate in physical activity, has a serious neurological condition preventing normal movement or walking ability, or has any severe medical conditions, such as cardiovascular disease. Participants will be recruited through advertisements on social media and through the local National Axial Spondyloarthritis Society (NASS). A minimum of 17 participants will be required per group (back pain and healthy groups), assuming 1-beta =0.90, alpha=0.05 and effect size $|\rho|=0.50$. The recruitment target will be 30 participants with long-standing back pain and 30 participants without back pain to test validity and reliability

in a laboratory setting as well as reliability and feasibility testing in the home environment[16]. If any participants withdraw from the study before laboratory testing, new participants will be recruited to achieve the total of 60 participants.

Methods of measurement

Our approach to the CVAS (Good Boost CV system, Good Boost Wellness, UK, 2021) involves a modified version of OpenPose, which is a computer vision algorithm trained to detect key landmarks on the human body within camera images[17]. Because it has been trained on many thousands of images, it is sufficiently robust to be used in almost any setting. For a given frame of image/video data, OpenPose returns predicted x,y coordinates for each body part and each human detected in the image. We use the x,y coordinates to compute metrics such as joint angles and distances (in pixels) between two body parts for a range of common clinical movements. To translate distance values into real-world distances, at the start of each trial, the user or a research assistant will hold up a calibration checkerboard parallel to the camera and at the same distance from the camera at which the movement is to be performed. Python's OpenCV package is used to automatically detect the corners of the checkerboard, and this information is then used to scale all distance values from pixels to centimetres[18]. The videos taken in the movement laboratory will be captured by a Logitech C920 pro HD webcam with a resolution of 1080p and a sampling rate of 30fps (©2021 Logitech, UK). The videos taken in the home setting will be captured by the participant's smartphone camera, tablet camera or webcam.

The reference test for the CVAS will be a standard axSpA clinical assessment by a physiotherapist[19]. The physiotherapist will be trained to perform standardised measurements of functional movement and range of motion tests relevant to back pain presentation. Since the CV-aided analysis is completed after the assessment, the physiotherapist is blinded to any results. Similarly, the CV-aided analysis is automated and completed separately from the assessment therefore all analysis is blinded from the physiotherapist measurements.

During the research visit within a university movement laboratory, all participants will first give their informed consent for participation, then answer demographic information and complete questionnaires related to pain, stiffness and functional limitation. The self-reported disease-specific questionnaires to be collected are the Bath AS Functional Index (BASFI), composed of 10 questions about functional limitation with final scores ranging 0 (no functional impairment) to

10 (maximal functional impairment); the Bath AS Disease Activity Index (BASDAI), composed of six questions pertaining to fatigue, spinal pain, joint pain/swelling, areas of localised tenderness and morning stiffness with final scores ranging from 0 (no disease activity) to 10 (severe disease activity); and the Bath AS Patient Global score (BAS-G) which asks about the effect of the disease on the person's well-being over the past week and the past six months on a visual analogue scale, 0 (no effect) to 10 (severely affected)[20–22]. Their baseline characteristics will be measured, including: height, weight, leg length and gait data. Gait data will be captured using an IMU (LPMS-B2) placed on projected centre of mass (L4) and analysed for spatiotemporal gait parameters (step length, stride length, gait speed, cadence, walk ratio and covariance)[23]. They will then perform a series of standard functional movements and range of motion tests that are commonly used in a physiotherapy assessment. They will first perform this index of tests as instructed and measured by the physiotherapist, then perform the same tests with the same instructions by the physiotherapist but captured by video recording for CV-aided analysis. Following the in-person laboratory visit, the participant will be given detailed instructions for completion of the same movements at home to capture on video. Participants will be given the same calibration checkerboard used in the laboratory to use at home. The videos taken at home will be uploaded to a secure site for post-hoc processing by the CVAS.

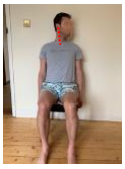
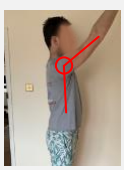
Outcome measures for criterion validity

Videos will be captured of the following physical tests in which the participant completes two repetitions: lumbar side flexion, lumbar forward flexion, tragus-to-wall distance, cervical rotation seated, hip internal rotation seated, hip abduction standing, shoulder flexion, chest expansion, posture and 5x sit-to-stand (5xSTS). These same tests will be captured on video by the participant in their home. Videos from both the laboratory and home will be securely uploaded and processed through the CVAS. The best of the two repetitions of each test will be used. The listed index of tests will also be measured by the physiotherapist who will also measure the following additional tests: Modified Schrober's, supine cervical rotation, and intermalleolar distance. See Table 1.

Feasibility

In order to measure the feasibility of the CVAS, several metrics will be collected to estimate the practicality and viability in both settings. The completion rate of outcome measures both in the lab and home environments will be recorded to understand internal and external barriers to implementation.

Table 1. Index of tests

TEST	DESCRIPTION (WHERE THE TEST IS USED)	EXAMPLE	CVAS IN LAB (2X REPS)	PHYSIO ASSESS -MENT (2X REPS)	CVAS AT HOME (2X REPS)
LUMBAR SIDE FLEXION	Active ROM test for standing lateral side flexion (BASMI and EDASMI)		✓	✓	✓
LUMBAR FORWARD FLEXION	Active ROM test for forward flexion (standard clinical test, adapted from BASMI)		✓	✓	✓
TRAGUS-TO-WALL	Standing global forward posture (BASMI)		✓	✓	✓
CERVICAL ROTATION (SEATED)	Active ROM test of cervical rotation (EDASMI)		✓	✓	✓
HIP INTERNAL ROTATION	Active ROM test of bilateral internal rotation in a seated position (EDASMI)		✓	✓	✓
HIP ABDUCTION	Active ROM test of hip abduction in standing position (adapted from BASMI intermalleolar test)		✓	✓	✓
SHOULDER FLEXION	Active ROM test of shoulder flexion (standard clinical test, adapted from BASFI)		✓	✓	✓

CHEST EXPANSION	Active chest expansion measurement from seated (BASMI and EDSAMI)		✓	✓	✓
5XSTS	Functional test of lower extremity strength by recording the time taken to complete 5 sit-to-stand repetitions (standard clinical test)		✓	✓	✓
STANDING POSTURE	Measurement of thoracolumbar spinal posture		✓	✓	✓
MODIFIED SCHOBER'S TEST	Active ROM test of lumbar flexion (BASMI)			✓	
CERVICAL ROTATION (SUPINE)	Active ROM test of cervical rotation in supine position (BASMI)			✓	
INTERMALLEOLAR DISTANCE	Active ROM test of hip abduction in supine position (BASMI)			✓	

Statistical analysis

Descriptive statistics of participant demographics and characteristics will be analysed. Data from the outcome measures will be tested for normality of data and compared between groups. Criterion validity will determined by Pearson's or Spearman rank and reliability via paired sample t-tests and interclass correlation coefficient (ICC 3,1 & ICC 3,k). Potential bias and agreement will be assessed via Bland-Altman plots. Validity between different data collection methods will be measured using Cronbach's alpha and Pearson's correlation or Spearman's rank correlation depending on data normality. Data will be analysed using SPSS version 26 or newer.

Discussion

The need for an automated, markerless system that measures important functional movements was the driving force behind this validation study. The study was designed to measure multiple dimensions of measurement properties and usability of the system. There were several main areas of the study that required particular consideration during the design: the index of measurements tested, the settings and administration of the measurements and the participants included.

First, the specific measurements included for testing were informed by the evolution of tools used to assess the mobility in people with axSpA, in particular, the BASMI and EDASMI. As the BASMI is the most commonly used tool, it was important that all tests were included or represented. Lateral side flexion and chest expansion were included for video capture, but cervical rotation in supine position, intermalleolar distance and Modified Schober's were not due to the practicalities of video angles and limitations of the CVAS. Cervical rotation with the participant in supine position would be impractical to perform in a home environment therefore cervical rotation in the seated position, as included in the EDASMI, was measured by video instead of the supine position. Intermalleolar distance was impractical for video both in the lab and at home, as the camera would need to be mounted quite high above a person while they laid on the ground; this test was replaced by bilateral hip internal rotation in the seated position which was part of the EDASMI. Lastly, capturing the Modified Schober's test would have required more than one camera angle in the lab and would have been infeasible in a home setting due to specific anatomical landmarks and measurements that need to be marked on the participant's back.

Second, for the settings and administration, we chose to test both in a movement laboratory with a musculoskeletal physiotherapist and in a home environment with the participant independently. In the lab, a measurement assessment by a musculoskeletal physiotherapist was used as the reference test to serve as a close representation of a true clinical assessment. Additionally, the physiotherapist will instruct the tests to be captured by video in order to ensure the movement is performed correctly with minimal compensatory movement patterning. In the second part of the study, participants will perform the same index of tests at home, capture them on video, and upload the videos. This will serve as a test for the feasibility of the method at home in order to identify areas of error that could arise due to camera set-up, execution of the proper movement,

time dedicated to the process, and the acceptability of the whole experience. As there are many variables occurring in an unsupervised home environment, this setting cannot be validated in this particular study design, but the reliability can be tested and the practicalities better understood. Lastly, participants included in the study will be both people with long-standing back pain and diagnosed axSpA as well as healthy controls without back pain. Clinically, people with long-standing back pain and specifically axSpA, demonstrate limited range of motion therefore it is important that this CVAS be tested on a spectrum that includes a clinically relevant population. Including both of these groups also serves to shed more light on the acceptability and feasibility of testing in an unsupervised home setting in a larger group. Additionally, a healthy group will serve as a control to compare validity and reliability results.

Overall, this study has made many considerations to the design of the protocol in order to get a broad picture of the measurement properties and feasibility of the CVAS. This completion and results of the study will be a foundation for further research and potential future use in the clinic or home setting.

Trial registration: ClinicalTrials.gov Identifier: NCT04895826

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