Video Article

Movement Retraining using Real-time Feedback of Performance

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Abstract

Any modification of movement - especially movement patterns that have been honed over a number of years - requires re-organization of the neuromuscular patterns responsible for governing the movement performance. This motor learning can be enhanced through a number of methods that are utilized in research and clinical settings alike. In general, verbal feedback of performance in real-time or knowledge of results following movement is commonly used clinically as a preliminary means of instilling motor learning. Depending on patient preference and learning style, visual feedback (*e.g.* through use of a mirror or different types of video) or proprioceptive guidance utilizing therapist touch, are used to supplement verbal instructions from the therapist. Indeed, a combination of these forms of feedback is commonplace in the clinical setting to facilitate motor learning and optimize outcomes.

Laboratory-based, quantitative motion analysis has been a mainstay in research settings to provide accurate and objective analysis of a variety of movements in healthy and injured populations. While the actual mechanisms of capturing the movements may differ, all current motion analysis systems rely on the ability to track the movement of body segments and joints and to use established equations of motion to quantify key movement patterns. Due to limitations in acquisition and processing speed, analysis and description of the movements has traditionally occurred offline after completion of a given testing session.

This paper will highlight a new supplement to standard motion analysis techniques that relies on the near instantaneous assessment and quantification of movement patterns and the display of specific movement characteristics to the patient *during* a movement analysis session. As a result, this novel technique can provide a new method of feedback delivery that has advantages over currently used feedback methods.

Video Link

The video component of this article can be found at http://www.jove.com/video/50182/

Introduction

Any significant change to the neuromuscular or musculoskeletal structure of the lower limb will likely have an impact on the characteristics of movement and associated physical function. Accordingly, improvement in physical function is an important outcome of any rehabilitation intervention. Normal repetitive movements such as walking are generally governed by motor programs that contain the necessary control information needed to activate muscles with the correct intensity and timing[1]. These motor programs are necessary to improve the automaticity of movement, thus reducing the amount of control devoted to movement and permitting attention to be paid to other higher level tasks. However, given the role of motor programs in movement and the fact that these programs are refined over a number of years, changing movement performance after injury or disease is a challenging venture.

Traditionally, movement retraining interventions have been predicated on providing sufficient feedback of movement performance to ensure that the new information is incorporated into the new and evolving motor program. Simple, yet effective, approaches include verbal feedback with global instructions (*e.g.* "bend more", "keep your knee straight") as well as mechanisms of providing visual feedback such as use of a mirror or video recording devices. Though these indirect strategies are useful, especially in clinical settings with limited resources, they are limited by their difficulty in providing discrete and quantifiable measures of movement variables. As a result, supplementing these techniques with additional more direct methods of feedback will likely enhance the motor re-learning desired.

There is much acceptance in the research and clinical communities that providing feedback of discrete, quantifiable outcomes of movement characteristics can improve performance during a movement retraining intervention. For example, instantaneous visual or auditory feedback of muscle activation intensity using electromyographic biofeedback devices has become a mainstay in the rehabilitation of movement, particularly in people with stroke[2-3], cerebral palsy[4], or chronic hemiplegia[5]. In contrast, feedback of movement kinematics (joint and segment angles) has proven to be less utilized due to a difficulty in assessing and measuring these outcomes quickly and accurately. Indeed, though quantitative, laboratory-based analysis of motion features prominently in biomechanics research and has begun to be incorporated into the clinical setting, the vast majority of motion analysis usage is reserved for offline analysis after testing. However, there is an increasing number of studies in the literature that are using new technologies to provide feedback of gait measures as a means of improving the effectiveness of movement retraining[6].

One pathology that is currently being investigated for usage of real-time biofeedback capabilities integrated with standard motion analysis systems is knee osteoarthritis (OA). Recent studies have utilized real-time feedback of gait kinematics designed specifically to reduce the load passing through the knee joint, quantified using the external knee adduction moment - a recognized risk factor for OA progression[7]. For example, studies have utilized real-time biofeedback of magnitudes of thigh angle[8] or trunk angle[9-10]. Hunt *et al*[11] provided a real-time display of trunk angle in front of participants during walking trials and showed the ability to increase exhibited trunk lean within a single training session, with accompanied reductions in knee adduction moment magnitudes. In contrast, Barrios *et al*[8] conducted an eight-session gait retraining intervention focused on modifying dynamic frontal plane knee angle during stance and showed significant reductions in knee adduction moment values after the one-month intervention compared to baseline. These studies, and similar studies, have relied upon the ability to measure, analyze, and display the variable of interest to the patient on a continual basis. This burgeoning area of research has clinical implications for patients with a variety of pathologies that impact movement characteristics. Using examples of kinematic alterations relevant to osteoarthritis (OA) of the knee, the purpose of this paper is to describe methods required to conduct a movement retraining intervention using real-time biofeedback of walking performance.

Protocol

1. System Preparation

1. Clear the capture volume of any reflective material that may be observed by the cameras. This decreases the chances of actual skin-based markers being confused with stationary background markers during the movement testing and improves the overall accuracy of the session.
2. Calibrate the cameras by aiming all cameras on stationary markers at fixed positions within the laboratory. Extend the static calibration to dynamic movements using moving markers placed at known distances. Be sure to cover as much of the capture volume as possible to optimize the calibration.
3. Organize all materials (reflective markers, measurement devices, etc.) to be used for patient preparation. This improves efficiency during testing and reduces patient burden.

2. Patient Preparation

1. Expose as much skin as possible over the joints and body segments intended to be measured. Minimize the amount of loose fitting clothing and ensure that any pieces of clothing that may interfere with the ability of the cameras to visualize the reflective markers are constrained. This can be done using tape or clips. Whenever possible, ensure that markers are affixed directly to the skin.
2. Prepare the skin for marker fixation. Shaving or abrading the area may be necessary in instances where hair is present or when the skin surface is excessively sweaty or oily. Wiping the area clear using rubbing alcohol or a similar liquid can be useful. These steps are important to maximize adherence between the marker and the skin, and to prevent markers from falling off.
3. Palpate for key anatomical landmarks based on the marker set to be used. Marking the skin at the actual landmark will improve accuracy for marker placement and provide information necessary in cases of markers falling off during assessment.
4. Affix reflective markers over the anatomical landmarks according to the specifications of the marker set. Most marker sets will include a minimum of 12-15 markers placed bilaterally over the lower limbs and various anatomical landmarks of the upper body. It is important to note that the ability to re-create actual skeletal movement will depend on the positioning of skin-based markers. As such, careful consideration must be made when determining the biomechanical model to be used.
5. Take measurements for important anthropometric data, if required. Depending on the biomechanical model, these data may be needed to calculate segment lengths, positions of joint centers of rotation, and overall inertial properties of the moving segments and limbs during offline processing of biomechanics data.

3. Motion Analysis and Delivery of Real-time Feedback

1. Have the subject stand in the middle of the capture volume for an initial static trial lasting approximately 3 sec. This trial is necessary to ensure that all relevant markers are visible and to calculate segment orientations.
2. Using the data collection software, label all markers as appropriate and create a template specific to the anthropometric characteristics of the individual. Matching marker placement to the individual body size will improve the real-time tracking and analysis of data. It is especially important to create a model of movement that can incorporate redundancies of marker positioning. In instances where marker occlusion or drop-off occurs, the ability to utilize additional marker positions where appropriate to produce the appropriate kinematic characteristic and maintain real-time display without breaks in the data.
3. Perform an initial motion analysis trial lasting from 10-30 sec. This is required to obtain baseline data and can also be used as the first mechanism of providing feedback of results to the patient. Consultation with the patient regarding relevant findings is important to assist in the motor learning required when producing new movement patterns.
4. Have the therapist explain the purpose of the intended movement modification. This should include both biomechanical and clinical rationales for the modification and how it is unique to the given pathology. Demonstration of the movement modification by the therapist will enhance motor learning by the patient. The movement modification will typically be determined based on the biomechanical and clinical presentation of the patient during treatment, or the research question to be examined if solely for research purposes.
5. Begin the movement retraining session. If using a treadmill, allow the subject to choose their own preferred speed and provide a couple of minutes to reach a steady-state. This also allows the patient to become familiar and comfortable with the equipment, experimental set-up, and protocol.

6. Provide feedback to the patient during performance of the movement. This can take the form of many different approaches, and combination of these is beneficial during early training. Start with less technical methods such as verbal feedback and progress to real-time biofeedback. Utilization of real-time biofeedback should always include clear display of a maximum of one outcome variable at a time.
7. Provide sufficient time for the patient to practice the new movement. Effective motor learning is not achieved instantaneously. Instead, constant practice of the new movement characteristics will assist in ensuring re-formulation of the motor program responsible for that movement. A typical retraining intervention may require 8-10 focused training sessions, each lasting between 30 and 60 min.

4. Patient De-briefing and Subsequent Training Sessions

1. Discuss the important findings and outcomes of the session with the patient. Important factors to focus on should include variability in performance, adherence to the prescribed movement modification and further description of the rationale and importance of the modification.
2. Obtain input regarding the session from the patient. Given that each patient's preferences will likely differ, it may be necessary to modify the delivery of the intervention for a given individual. These should be identified early to optimize effectiveness.
3. Determine the plan for subsequent training sessions, if necessary. If a multi-session intervention is chosen, subsequent training sessions should use a faded feedback approach to enhance motor learning. Provide less overall feedback and alternate between time blocks of feedback and no feedback in future sessions.

Representative Results

An example from a single movement retraining session focusing on increased lateral trunk lean angle in a patient with knee OA is shown in **Figure 2**. After approximately 15 min of training using a combination of verbal and mirror-based feedback of performance, the patient was provided with real-time data pertaining to the amount of lateral trunk flexion. Training with this method continued for an additional 10 min. During normal (unmodified) trials, the patient exhibited a self-selected amount of lateral trunk lean of approximately 2° (see peak of dotted line around 20% of stance). During modification trials, the patient was instructed to achieve a peak lean value of 6°, as depicted by a target area on screen. As can be seen in **Figure 2**, the modification of the gait pattern utilizing an increase in lateral trunk lean was not associated with an appreciable change in the overall pattern. Rather, the patient exhibited an increase in lateral trunk lean throughout the gait cycle.

The resultant effects on knee joint loading - as quantified using the external knee adduction moment - can be seen in **Figure 3**. Though not provided as visualized data to the patient, the biomechanical consequence of increased lateral trunk lean is a reduction in the knee adduction moment, potentially shifting the load within the knee joint[9,12]. Again, the general pattern of the knee joint moment - and subsequent loading within the joint - did not differ appreciably between the normal and modified trials. Instead, the magnitude was reduced throughout.

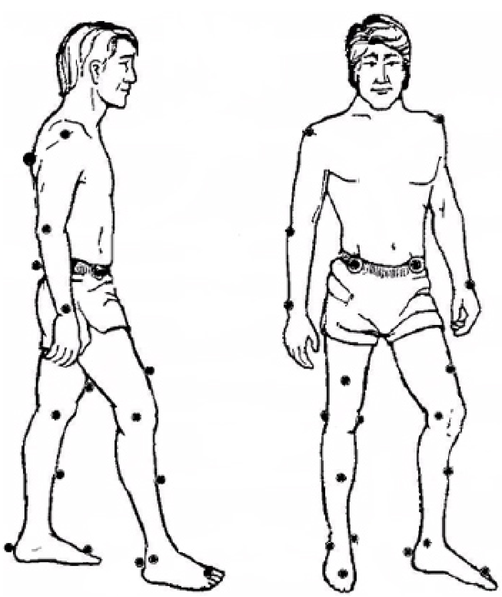

Figure 1. Basic marker set used for motion analysis testing. Black dots represent positions of reflective markers placed over specific anatomical landmarks. More complex marker sets are used when assessing joint and segment movements in more detail.

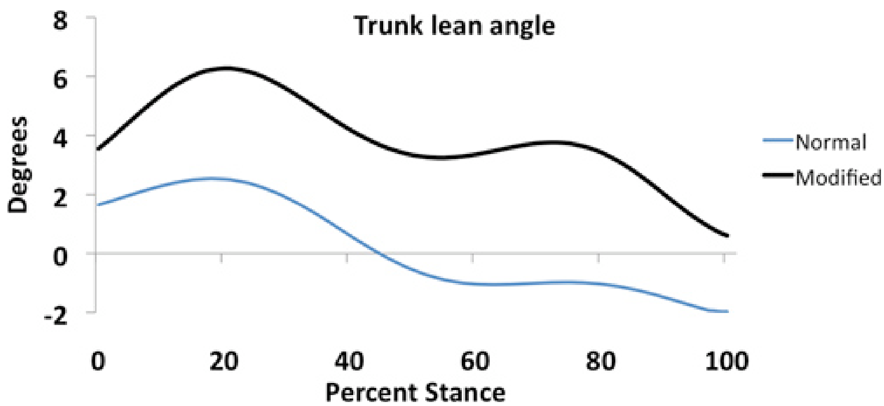

Figure 2. Sample lateral trunk lean angle during a normal walking trial (dotted line) and a trial where the patient was instructed to obtain a maximum amount of lateral trunk lean of approximately 6° (solid line). Real-time lateral trunk lean angle was displayed in front of the patient at all times. Data depicted are from a single stance cycle where 0% is initial contact of one limb and 100% is the toe-off of the same limb.

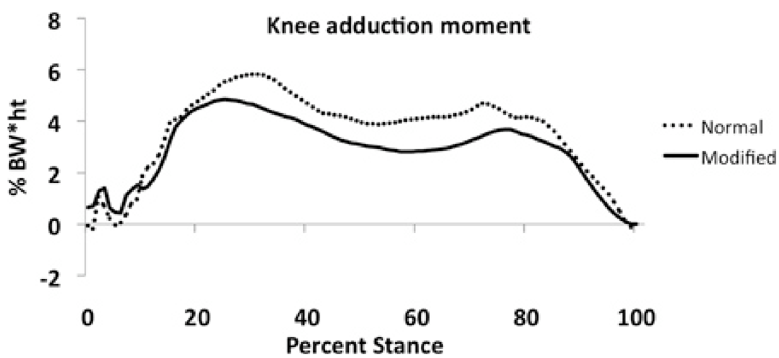

Figure 3. External knee adduction moment values throughout stance during a normal walking trial (dotted line) and one in which the patient was instructed to increase their amount of lateral trunk lean (solid line). Values are presented normalized to time as well as to body size (percentage of the product of body weight and height - %BW*ht).

Discussion

Real-time feedback of performance during movements such as walking can be a valuable adjunct to standard motion analysis approaches. Though in its relative infancy, research into specific and discrete movement modifications will certainly benefit from the ability to produce the desired modification with accuracy and in real-time. For example, if the patient requires a specific amount of movement modification, this amount can be measured and provided during the actual movement. The approach presented here can be used to test novel approaches to movement modification as well as refinement of existing protocols for a wide range of patient populations.

The accuracy of the data collected and the subsequent ability to achieve discrete modifications in movement parameters are dependent on a number of factors. Most importantly, motion analysis of any sort is reliant upon the assumption that the observed/measured movement is indicative of the true anatomical movement. As is, the skin-based markers are meant to provide a visual representation of specific underlying anatomical landmarks. Accordingly, to ensure that the captured movement accurately reflects the actual movement of the underlying skeleton, much care must be put into the choice of marker positioning. There are many different biomechanical models currently utilized that each has slightly different marker placements in an attempt to best track the movement of the skeletal system. Care must be taken when choosing a biomechanical model - a thorough discussion of these models is beyond the scope of this paper. Finally, regardless of the model used, adherence to accurate placement of the markers must be maintained. The importance of making extra effort to ensure this accurate palpation and subsequent marker placement cannot be overstated during movement retraining trials involving real-time biofeedback of movement performance, or any motion analysis trial for that matter.

The ability to track the movement of the body segments and joints is also dependent on the technical specifications of the camera system as well as the integrity and behavior of the skin-based markers. For instance, the magnitude of reflectivity or occlusion of vision of markers (for instance, if covered by loose fitting clothing) will negatively impact the data collected and provided to the patient. As indicated above, creation of segments in the biomechanical model that incorporate marker redundancies whenever possible in cases of "primary" marker occlusion or drop-out will ensure maintenance of the real-time data. Though higher resolution and more focused cameras will certainly decrease error when tracking movements, one must decide on the acceptable level of error for the intervention. While discrete (exact amount) modification of the chosen movement parameter is likely the goal in research settings, less exact modification may be necessary in the clinical setting. This reflects the need to be precise when researching the mechanisms of action for a given modification (and, indeed, the technical advantages of laboratory-based motion analysis systems), while also understanding the resource, time, and equipment limitations when implemented clinically. Though this does not preclude the use of exact modifications clinically, an assessment of limitations must be made when utilizing this approach in any setting. Further, though methods using a passive-reflective motion capture system have been described in this paper, the same issues of capturing and displaying accurate movement information remain valid regardless of the system used. For example, active marker systems or those utilizing wearable devices (*e.g.* electrogoniometers, accelerometers) still rely on the ability to construe skeletal movement and analyze effectively. The process of accurate collection, analysis, and display of information remains the same for any system.

Regardless of desired accuracy, accurate calibration of the system is required before any motion analysis or movement retraining session. This step is required to ensure that the positions of the cameras with respect to each other are known. It also provides an opportunity to ensure that all cameras are capable of visualizing the intended capture volume. For example, if vision from one camera is occluded due to another object (*e.g.* a table or chair), it is better to detect it during the calibration stage rather than the actual motion analysis stage. The calibration process will result in the determination of the magnitude of position and detection error of the system on that particular day. The maximum allowable error will depend on the technical specifications of the system as well as the preferences of the users. Calibration errors above these thresholds dictate re-calibration of the system.

There are a number of future applications of this technique for both research and clinical outcomes. The ability to examine the effects of immediate changes in a variety of biomechanical variables on movement function can provide valuable information necessary to understand better the mechanisms of movement. Thus, theoretical knowledge of functional biomechanics can be greatly enhanced through use of this technique. Indeed, one of the advantages of using real-time feedback of performance - even if a movement retraining intervention is not utilized - is the ability to detect any errors *during* the data collection session, rather than offline after completion. This will certainly improve the efficiency of movement analysis research.

The advantages of real-time biofeedback of movement and subsequent retraining must be weighed against the disadvantages of this approach. First and foremost, there is a substantial cost associated with any motion analysis system. Additional software and equipment costs or programming burden need to be factored in when adding real-time biofeedback capabilities. In addition, potential downtime due to technical difficulties of the system must also be anticipated at some point during usage. Conventional approaches such as using a mirror or video capture are significantly less likely to be impacted by downtime. Finally, given individual differences in motor learning styles, some individuals may not necessarily benefit from real-time biofeedback. Identification of these non-responders early is essential. A thorough understanding of motor learning principles is required to optimize outcomes during and movement modification intervention. For example, incorporating both knowledge of results and knowledge of performance during retraining can be effective to promote learning, and utilization of a faded feedback paradigm may assist in retention of performance in the longer-term.

Though the potential impact is clear from a clinical perspective, a number of questions still need to be addressed before wide scale movement modification strategies should be implemented within the clinical setting. First, though the local biomechanical effects are beginning to be well known, the effects of these modifications on clinically-relevant outcomes such as pain and function are yet unknown. The exact specifics of the movement modification will depend on the impairments associated with the pathology and the clinical and biomechanical characteristics of the individual patient. For example, the required movement modification parameters will likely differ between those with knee OA compared to someone who had a stroke of spinal cord injury. Further, increasing lateral trunk lean in someone with knee OA who already exhibits large amounts of lean may not be effective. More research is also needed to examine if changes in joint biomechanics translate to clinical improvement. Conducting longer-term interventions will provide valuable information regarding the feasibility (especially in the older population), adherence, and effectiveness of movement modifications. It will also provide the ability to monitor changes in biomechanics and symptoms at other joints to assess the risk of negative consequences of these modifications. Finally, though studied as a stand-alone treatment to test efficacy, clinical implementation of these modifications will ultimately be part of an overall treatment strategy. For example, treatment for knee OA will still involve muscle strengthening, range of motion exercises/stretching, and aerobic conditioning. Movement retraining utilizing real-time biofeedback can play an important role as an adjunct therapy approach as an effective means to optimize joint biomechanics and overall physical function. How movement modification would fit into clinical management, and how it could be combined with other interventions has yet to be determined.

Disclosures

No conflicts of interest declared.

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