Physical Medicine and Rehabilitation - International

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Austin Publishing Group

Special Article – Gait Rehabilitation

Sensor-Based Gait Rehabilitation for Total Hip and Knee Replacement Patients and Those at Risk of Falling: Review Article

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Received: December 04, 2015; **Accepted:** December 24, 2015; **Published:** December 28, 2015

Abstract

Recovering a normal gait after injury or maintaining a normal gait as people age is critical to maintaining mobility and health in later life. This review looks at the evidence relating to recovery of a normal gait after total hip or knee replacement and suggests how this may be improved using a sensor based approach. Conventional methods of monitoring gait use an optical gait laboratory, which is both costly and time consuming and therefore it is not a routine procedure for people in a clinical or home based setting. Unfortunately, all the evidence suggests that most people who undergo joint replacement do not recover a normal gait and this has an effect on their health. This suggests that people tend to stop the rehabilitation phase too early and this may be associated with a lack of monitoring. Recently, sensor-based system have been used to monitor joint replacement patients and arrived at the same conclusions as the optical gait laboratory trials, and therefore such a system can be used with confidence in the general clinical setting. Pilot studies have been carried out using these sensors, one following a patient recovering from a total hip replacement (THR) for 8 months and the second a two year longitudinal study following a group of elderly people at risk of falling. Both studies show that monitoring improves the outcome, with the THR patient recovering a normal gait and all 11 people at risk of falling remaining mobile with no falls over the two year period. This indicates that, with the advent of sensor based monitoring; gait rehabilitation can be applied in a broad range of situations, improving patient outcome and satisfaction.

Keywords: Gait monitoring; Sensor; Ageing; Total knee replacement; Total hip replacement; Falls

Abbreviations

THR: Total Hip Replacement; TKR: Total Knee Replacement; OA: Osteoarthritis; ROM: Range of Motion

Introduction

There are a number of times in people's lives when gait rehabilitation may be necessary, for example after a knee injury, a joint replacement, a stroke or a fall. Each of these would require a different form of rehabilitation, but in essence the goal is the same, to recover normal mobility. If this is not achieved then there may be repercussions later in life, for example a further joint replacement, additional falls or a complete loss of mobility. Since mobility has a fundamental impact on our quality of life, gait rehabilitation should be recognized as critically important to a person's well-being. However, when talking to health professionals it is clear that many feel that you simply cannot retrain a person to walk properly and therefore have to accept the consequences of a poor gait. This clearly is not true as people who have suffered a stroke that affects their walking can be retrained to walk again. So, the limitations must be in our ability to detect subtleties in the gait pattern that the eye cannot see, provide relevant exercises and then monitor progress. The result is that many people who have suffered injury or illness end up with an abnormal gait, and from the evidence presented below this can have a significant long-term effect on their health.

Current practice relating to gait rehabilitation relies on an assessment by a physiotherapist. This may include such activities as timing a person standing from a chair and then walking a certain distance (get-up-and-go test), determining the distance they can cover over a set period, or checking the static range of motion of various joints. However, whilst timing may reveal there is a problem with the gait, it does not help to identify what it is. Results from clinical studies have shown that static range of motion at joints does not equate to the dynamic condition of walking, so can be considered almost an irrelevant test for monitoring gait.

The rapid advancement in body worn sensors means that sensors can be used to monitor gait quickly and far more accurately than the eye; this data can then be used to guide the rehabilitation phase and improve outcomes. Unfortunately, to date this approach has received very little attention, particularly with physiotherapists.

Evidence of Poor Gait Rehabilitation

The effects of poor gait rehabilitation, focusing on hip and knee replacement surgery and falls in the elderly, is covered in studies published over the last 20 years. For the purpose of this study, when

Citation: Hodgins D and McCarthy I. Sensor-Based Gait Rehabilitation for Total Hip and Knee Replacement Patients and Those at Risk of Falling: Review Article. Phys Med Rehabil Int. 2015; 2(10): 1073.

referring to poor gait, the data obtained from a study on healthy people of all ages has been used as the reference [1].

Outcomes from Total Hip Replacement

There are a number of papers [1-7] on the gait characteristics of patients who have undergone a total hip replacement (THR). All of these studies were carried out between 6 months and 10 years post-op and most used precision optical tools for the measurements. Walking speed is resumed one year post THR, but the gait is still asymmetric and likely to place incorrect loading on other joints [2]. Other studies support the statement that normal gait has not be obtained, [3-5] and one also states that speed is also below that of a normal person [6]. In all cases it is shown that the movement on the unaffected side, which is the patient's own reference, is also reduced post surgery, and this means that the stride length is reduced. A further paper supports the conclusions from all other papers that the patient has not recovered a normal gait at 6 months post op, yet the patient's outcome measures indicate a success and also their activity level has increased [7]. This means that the patients are walking more frequently with an abnormal gait, which puts incorrect loading on the other joints. A similar study was undertaken using motion sensors where it was found that at one year post-op the hip ROM on the non-affected side had reduced and only 50% of the patients had a normal gait [8]. The effect of incorrect loading on the contralateral knee for THR patients is important, as it is known that patients are more likely to suffer with knee OA in the contralateral knee. One study found that dynamic loading on the contralateral knee was significantly higher than the ipsilateral knee [9]. This had the effect of increasing the bone density at the knee joint and supports the notion that alterations in dynamic joint loading may precede the onset of asymptomatic knee OA.

Outcomes from Total Knee Replacement

Knee osteoarthritis (OA) is the most common reason why a patient will have a total knee replacement (TKR). Identifying knee OA early provides the opportunity for less invasive treatment, but unfortunately no simple diagnostic tests are currently offered to enable individuals to identify the condition early enough.

Concerning the variables that are affected by knee OA, stance flexion is directly related to the severity of knee OA and flexion in swing is affected when the condition becomes severe [10]. A further study confirms that knee movement during any activity is considerably lower than for age matched controls, but the static flexion is comparable, indicating that load bearing inhibits movement, and that a static knee ROM is not suitable for determining the dynamic performance of a patient [11]. Data from a group of subjects with mild, moderate and severe knee OA, using an optical system shows that knee ROM and peak vertical ground reaction force both correlated with severity [12]. For knee ROM there was minimal difference from mild to moderate but significant difference from moderate to severe. Another study also concluded that people with early stage knee OA had reduced knee flexion in stance using a sensor-based tool [13]. Pre-op TKR patients with late stage knee OA were monitored using a sensor based system and it was also found that the knee flexion in swing and stance were both affected [14], confirming the results from other studies from the optical gait lab. The gaits of patients with medial compartment knee OA were compared to a healthy control group and it was found that the two groups walked at similar speed but their gait profiles were very different [15]. The patients with knee OA had high knee abductor moments and hence high hip abductor moments and they compensated by working the hip adductor muscles harder. It was proposed that a suitable rehabilitation program for this group would be to focus on the hip adductors rather than the quadriceps, which is the current general procedure. In summary, early stage knee OA reduces knee flexion in stance and late stage knee OA reduces knee flexion in swing and stance. For medial compartment knee OA the knee abductor moments are higher and this affects the hip joint.

A study where patients were measured using an optical system at 4 and 12 months post-op to ascertain whether the 4 months gait data could be used to predict if a person would not recover well concluded that dynamic knee flexion was a good predictor at 4 months and this information could be used to help guide the rehabilitation process [16]. Another study measured the outcomes from a small group of elderly patients with bilateral knee replacements at between 2 and 5 years post-op, where the two replacements were from different manufacturers [17]. It was found that the knee ROM was lower than for healthy controls and there was often significant asymmetry. However, this did not correlate with the type of implant, so it was patient specific. In another study the gait was monitored on patients at the pre-op and 8 weeks and one year post-op, using a sensor based system [14]. The findings were that only 40% of the patients had resumed a normal gait, and for the rest it was the knee flexion in swing and or stance that had not recovered.

These studies all conclude that knee OA can be identified early and there are possible strategies that could be adopted to help people manage their condition. For those patients that go on to receive a TKR, a large percentage do not recover a normal gait.

Falls in the Elderly

The risk of falling increases with age and one in three adults over 65 falls each year [18]. Mobility of the elderly relates directly to the number of falls, with one of the common causes of falls in the elderly related to gait deficiencies [19]. As with the joint replacement patients, gait is monitored visually and may be supported by assessments of gait such as the Berg Balance test [20] and the Timed up and Go test [21]. Simple speed tests do not identify gait deficiencies and hence objective advice on how to improve cannot be provided. For example, two people may have an identical speed but one has an asymmetric hip movement that changes loading and balance [1]. Similarly, people with medial knee OA walked with the same speed as healthy controls but had abduction moments at the knee and hip and these affect the balance [15]. All of these conditions would require different management in order to help the individual and hence it is essential to understand the underlying gait parameters for each individual. To date no studies have specifically focused on correlating gait parameters of the elderly who are considered at risk of falling, and as such only generic exercises can be proposed.

Numerous studies investigate the correlation between walking speed and falling [22]. One study looked at the gait profile and found that speed is not age dependent but medial-lateral movement is, and it is this that affects the likeliness of falling [23]. Another study found a correlation between quadriceps strength and gait speed in older people [24]. These studies provide further support that there are a wide variety of reasons why older people have problems with walking.

Rehabilitation

The discussions relating to hip and knee replacement patients indicate that a large number do not recover normal mobility, which suggests that the rehabilitation phase was not optimal. The studies also reveal that for those patients who do not resume a normal gait, further problems likely to occur. For example, hip patients are likely to get knee OA on the contralateral knee, and knee patients are likely to get hip problems on the ipsilateral hip [9,15]. Around 50% of the older people will fall as a result of poor gait, and many of these may be people who have not recovered from a hip or knee replacement.

There are five different ways of monitoring people walking:

Analysis by the human eye and simple tests

These tests require no instrumentation; the outcomes are limited to ascertaining whether the individual has a problem with walking or balance, but not what the problem is or therefore how it can be improved.

Foot pressure and temporal data monitoring systems

This type of test requires equipment that may be portable or fixed. The temporal data provides some insight in to how quickly an individual moves and this can be compared to a normal healthy reference. However, it provides no information on what causes the movement to be outside limits and therefore what the individual can do to improve it.

Video

This requires simple equipment, normally just a video camera and treadmill in order that the person remains in the same position in relation to the camera. The accuracy of this process is dependent upon the alignment of the video in relation to the individual under test, the resolution of the video and the accuracy of defining anatomical markers by the person doing the assessment. Typically, these combined errors could be over 10^0. Generally the video is focused on the foot and ankle, with the aim of defining how square the foot is at the beginning and end of load by measuring the out of plane motion of the foot and ankle. Seldom will the individual have an assessment made of the knee or the hip or any movement in the sagittal plane. Furthermore there will be no information regarding the range of motion of joints or segments in either the sagittal or coronal planes or timing of any aspect of the gait cycle. So, as simple assessment with a video can provide limited information on how the foot lands, in a similar way to pressure mats. All the limitations of the pressure mat system apply to this type of assessment. In addition, although the equipment is simpler it provides less information, missing all temporal data relating to the stride.

More recently companies have developed health applications for the Kinect system, which is video based. Whilst the user experience is more user friendly, it still suffers from exactly the same limitations as those for any other video system.

3D Optical gait analysis

3D optical gait analysis is considered to be the Gold Standard for testing a person's movement, and this can include upper body movement as well as their gait. The complexity of the system is dependent upon the requirements, but for gait, where both sides of the limbs must be seen and sagittal and coronal information is required, typically the minimum number of cameras required is 6. There are approximately thirteen major gait laboratories located in hospitals around the UK and there are also some major gait laboratories in Universities and these typically cost £0.5-1M to set up and require a highly skilled person or persons to run it. The time required to complete an assessment is typically half a day, with at least one skilled person present. A report will be available some time later, due to the extensive work required to analyse the optical data. Also, most consultants and individuals find it difficult to understand the information provided in the report. The cost and timescale for carrying out this type of test therefore makes it unsuitable for guiding rehabilitation.

An enhancement to the optical system is one known as MOTEK. This uses the optical system to monitor movement of a person on a treadmill and provides real time feedback to the person using a virtual reality display. The cost of this system and the time to set up for a training session makes this approach prohibitive for general rehabilitation following joint replacement or for the elderly at risk of falling.

Sensor based approach

The newer, alternative gait analysis technique uses inertial sensors, which are mounted directly on to the patient. This approach can be quick, accurate and provide certain key kinematic parameters with comparable accuracy to optical systems. In addition, a specialist laboratory is not required for sensor-based systems. These systems can be used anywhere, including care homes, out-patient clinics and day centers. For this reason it is feasible to use this approach to help guide rehabilitation.

One review of 21 publications, some of which were themselves reviews, examined the evidence for different rehabilitation methods [25]. Some of the reviews concluded that it was not possible to ascertain which type of physiotherapy was beneficial due to lack of evidence, and the conclusion was that there is insufficient evidence to suggest which type of physiotherapy, or whether any physiotherapy is beneficial. In another study, patients who had undergone THR were placed in two groups, one having home exercises and the second having centre based exercises over an 8-week period [26]. The conclusion was that both groups improved and the difference was minimal, indicating that home exercises are as effective as those run by a physiotherapist. Unfortunately the outcome measure did not include kinematic gait data; instead they focused on the conventional tests such as the 6 minute walk test and sit to stand.

It is believed that if individuals were given exercises to address their specific gait deficiency then the outcomes would be improved. However, this has not been proven, which is why many professions consider it is not possible to make changes, particularly with older people.

Improving Outcomes using a Sensor-based Gait Monitoring System

The evidence clearly shows that a large percentage of hip and knee replacement patients do not recover a normal gait, and that gait deficiency often lead to further joint replacements or falls. Sensor based systems have been shown to be able to measure gait to a comparable accuracy [1] and these systems can be used in the clinic, a day centre, or even in the home. This type of system has the potential to improve outcomes because: 1) Data is available at the time of test; 2) output is provided in a form that is intelligible to both the therapist and the patient; 3) a traffic light system can quickly highlights problem areas; 4) patients are motivated by being able to follow their progress.

The published evidence, therefore, indicates that gait deficiency can be detected after THR and TKR, and in elderly people at risk of falling. The hypothesis can that be put forward that simple and precise measurement of gait could form the basis of designing targeted exercises to improve gait and mobility. Two preliminary studies have been performed to test this hypothesis.

Elderly at Risk of Falling

Gait parameters for healthy people of all ages have already been published [1] and it was found that there was little change in gait with age up to 80 years old. The aim of the study were to explore the potential of using objective gait data to support personalized exercise for 11 older people considered at risk of falling over a two year period to help prevent falls [27]. This was to be achieved using a sensor based gait analysis system (GaitSmart, ETB, UK).

The range of motion (ROM) of the knee and the symmetry between the left and right knee ROM were analysed, requiring just four sensors placed on each thigh and shank. This provides a good indication of stride length plus how well the individual picks their feet up, reducing the risk of tripping. Older people may reduce their thigh range of motion and this reduces their knee angle and stride length [1,28]. The symmetry indicates whether the individual is balanced. This minimises the amount of data that the individual needs to understand so that they can act upon the information.

The results showed that the eleven people who were monitored over the 130 week period responded positively to instruction on exercises based on their gait data. This resulted in their gait changing with time, bringing the individual back closer to the normal range. None of the eleven participants exhibited any deterioration with time, there were no falls and all remained active. The regular monitoring provided them with objective data that they and the Balance Class teacher could act upon. Each individual had a different condition which changed with time, and this meant that each needed their own customised exercise regime. The gait data provided the teacher with additional information regarding the severity of the condition and perhaps more important, a starting point for the individual. Regular monitoring ensured that they maintained their exercise regime and understood why it was necessary to do so. For one of the individuals with a worsening gait, it was only once she understood the severity the problem through the objective data that she responded and followed the guidance of the teacher.

Patient Who has Undergone a THR

A case study using body worn motion sensors has been undertaken with one 74-year-old male THR patient. This study followed a single patient from pre-op to 7 months post-op, with the patient measuring themselves at home twice a week [29]. The data was used to motivate the patient through the rehab phase, by presenting him with quantified improvements in his gait. This was done in addition to the physiotherapy received over the first 6 weeks. The outcome shows that the most rapid improvement was made in the first 10 weeks, but the gait continued to improve gradually over the following 20 weeks. After 30 weeks the asymmetry between the affected and non-affected side was minimal, and the range on both sides was well within normal limits and significantly above that quoted in the other reference papers. Whilst this is only a sample of one it does demonstrate that objective gait data alongside standard physiotherapy can help an individual to recover a normal gait.

Summary

Gait rehabilitation is essential if people are to remain mobile and minimize joint replacements. However, the evidence to date indicates that a large percentage of THR and TKR patients do not recover a normal gait and this has repercussions. Alongside this many older people fall due to a poor gait, and although the link between poor recovery from joint replacement and falls has not yet been made, scientific evidence suggests that it is present. The rehabilitation phase is generally controlled by physiotherapists, who use their eye and simple timing tests. However, as clearly identified in the clinical studies, this approach does not provide the necessary information to design the right exercises for the individual or identify when problems still exist.

There are now sensor-based systems that can provide this monitoring accurately, quickly and in a clinical or home environment. With the development of such systems, it is now feasible to consider routine gait rehabilitation in large patient populations. Some preliminary results presented in this paper demonstrate the effectiveness of this approach and this now needs to be carried out on a much larger scale with well designed, randomised prospective trials.

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Phys Med Rehabil Int - Volume 2 Issue 10 - 2015
ISSN : 2471-0377 | www.austinpublishinggroup.com

Citation: Hodgins D and McCarthy I. Sensor-Based Gait Rehabilitation for Total Hip and Knee Replacement Patients and Those at Risk of Falling: Review Article. Phys Med Rehabil Int. 2015; 2(10): 1073.