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Preliminary Results for a Monocular Marker-Free Gait Measurement System

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PRELIMINARY RESULTS FOR A MONOCULAR MARKER-FREE GAIT MEASUREMENT SYSTEM

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Summary This paper presents results from a novel monocular marker-free gait measurement system. The system was designed for physical and occupational therapists to monitor the progress of patients through therapy. It is based on a novel human motion capture method derived from model-based tracking. Testing is performed on two monocular, sagittal-view, sample gait videos – one with both the environment and the subject's appearance and movement restricted and one in a natural environment with unrestricted clothing and motion. Results of the modelling, tracking and analysis stages are presented along with standard gait graphs and parameters.

1 INTRODUCTION

1.1 Motivation

This paper is presented as part of a gait measurement design project. The goal of this project is to design a system, for the use of occupational and physical therapists, which would capture and analyse human gait. Current methods of gait measurement involve complex marker systems and a multiple camera set-up, thereby requiring a dedicated gait laboratory and trained therapists, making the systems cumbersome and difficult to use. Here we have designed a simple single-camera system which is not only accurate but also has a low processing time and can be used remote from the filming location, thereby eliminating the need for patients to travel to a gait laboratory. It is hoped that the simplicity of the system will encourage both therapists and patients to participate in gait studies and make the most of the technology available.

1.2 Marker-based Systems

Marker-based systems are still the most readily used method of gait analysis. However, they are extremely difficult to use and problematic, requiring specific equipment and expertise. This makes the systems less portable and less accessible outside of a gait laboratory which can be a significant issue when patients are too unwell to travel. In addition, a gait laboratory can be a very intimidating environment, which can make patients feel uncomfortable – a major issue particularly when dealing with young children and elderly patients.

In order to avoid marker movement, markers cannot be placed on clothing as this will move relative to the joints and bones being marked. The patient must be stripped and the markers attached directly to their skin. This again adds to the discomfort that patients can feel in a gait laboratory environment. Many gait patients are elderly stroke victims who do not feel at all comfortable walking in their underwear. One of the major motivations of our design was to eliminate the need to strip the patient.

Even with experience and knowledge, marker placement is still a difficult task. The position of the markers will have a significant effect on the output of the system. Even slight inaccuracies, particularly around the joints, can cause the system to fail. Once the markers have been placed accurately to begin with, they must be kept in position as the subject walks. They must not interfere with the freedom of movement of the patient and the system must be invulnerable to marker occlusion. The equipment required for measurement can be uncomfortable to wear and can have a significant effect on the subject's freedom of movement. Active marker systems require a transmitter, power supply and wiring to be worn by the patient as they walk. Passive markers are often mounted on special supports or protruding sticks to make them more visible in the image. Again, this can restrict the subject's movement and limits the positions in which markers can be placed (for instance, protruding markers cannot be placed on the inside of the subject's legs as they will easily be knocked while walking).

This cumbersome equipment is not only difficult to attach but could have a significant effect on the movement of the subject. While passive marker systems are less intrusive, they require more markers to compensate for their vulnerability to occlusion. Since passive markers are reflective, they effectively disappear when they are blocked from the infra-red light. This happens quite regularly during walking as the subject's arm naturally swings back and forth, thereby occluding any markers around the pelvic region. All of these issues make a marker-based system difficult to design and operate. Instead, we envisage a system that will be so simple to use that patients could be monitored in any local clinic, hospital, surgery or even in their own homes.

In fact, occlusion is an issue even with marker-free systems. Many attempts at designing marker-free systems have been based on feature detection and tracking [1] or on apparent motion [2]. At the point of crossover of the legs, during the swing phase of gait, the image features become less well defined and it is difficult to identify any apparent motion. Although this is not technically occlusion, the result is the same: the tracking cues are lost. In developing a new marker-free system, this is a major consideration.

1.3 Marker-free Gait Analysis

There are currently many research groups striving to develop the first fully automated marker-free system. There are, in fact, already some commercially available marker-free systems, e.g. [3]. However, so far, none of the available systems is completely automated and they still require a gait laboratory environment, several measurements of the subject and/or manual intervention at various stages in order to operate reliably. While these systems may suffice in other applications, they have not been readily embraced by therapists as a better alternative to marker-based systems in monitoring pathological gait.

Although it may still be necessary to use specific equipment to acquire certain data, e.g. force-plate measurements, we feel that there is no reason that gait kinematics, the information gleaned from video data, cannot be measured remote from a gait laboratory. The greatest challenge from a motion analysis point of view lies in analysis of the lower limbs in the sagittal plane. In fact, this is also where the most useful information is gathered for diagnosis and interpretation of gait data. In some basic marker-free systems, the subject is required to wear different coloured stockings on each leg to distinguish the two legs from each other, e.g. [4]. This strays from the goal of a non-intrusive and completely marker-free system. The difficulties in the sagittal plane stem from the similarity in appearance and proximity of the two legs and from the speed change during the swing phase of gait.

As the legs cross during the gait cycle, the image of the moving leg becomes blurred and the moving leg becomes indistinguishable from the stationary leg. With standard motion tracking techniques, this can lead to motion vectors having erroneous zero values. This is why sagittal gait analysis is such a challenge when attempting automated motion tracking. Many current marker-free techniques are still being improved upon in this area. Review papers [5] and [6], covering the entire area of human motion capture including marker-based and marker-free analysis, can be consulted for a more thorough survey of the current state of human motion research.

1.4 Design Goals

With the interests of both patients and therapists in mind, we outlined the following goals for the project:

- The system must be completely automated requiring no excessive measurements of the patient and no manual intervention.
- The system must be simple to use.
- The output will be a complete set of sagittal plane gait graphs and parameters.
- The input will be a single AVI file containing a film of the patient walking.
- The gait video can be filmed in any reasonable environment without significant restrictions.
- The subject can be fully clothed in appropriate clothing.
- The subject can walk freely.

In addition, because this motion measurement system has a specific application, we can apply certain restrictions to our expectations:

- It is reasonable to expect adequate lighting and contrast in the filming environment.
- The data will be filmed from a stationary camera.
- The subject will walk from one side of the camera view plane to the other.
- The subject will be fully visible in all frames from head to toe.
- Clothing will not hide the subject's leg outline, for example, skirts may not be worn.
- The height of the subject is known.

In designing our system, we tried to meet as many of our goals as possible whilst minimising the restrictions on the system. An initial design attempt was made previously but the difficulty at the crossover of the legs during the gait cycle could not be overcome and the untracked leg had to be manually removed from each frame in order to provide results [7]. Since then, however, a method has been discovered which outlines the tracked leg in each frame, thereby distinguishing it from the untracked leg. This method has been integrated into the overall system and adapted to make it completely automated and robust. The result is a fully automated tracking system that succeeds in reaching our outlined goals.

2 IMPLEMENTATION

2.1 Segmentation

The human motion capture method used here is based on a method introduced by Nyogi and Adelson [8]. In their 'XYT' method, video frames from a stationary camera are stacked to create a 3D block with two of its dimensions representing horizontal and vertical directions and its third dimension being time (See Figure 1). A picture of the movement in the video is obtained by slicing the block in the XT direction. In the XT slice, the stationary background appears as vertical lines and objects moving horizontally across the camera plane appear as diagonal lines.

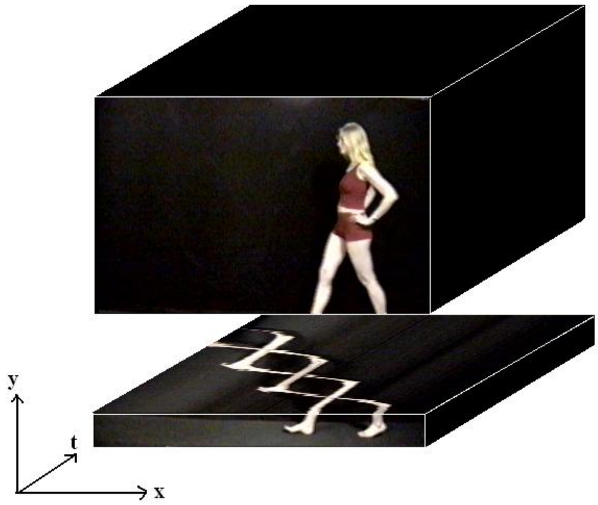


Figure 1: The XYT block for the gait laboratory sequence.

This image is particularly useful for recognizing and analysing walking because of an interesting characteristic of the leg motion. In the case of a sagittal view of a human walking in front of a stationary camera, a distinctly recognisable braided pattern is observed in slices around the leg height (see Figure 2). The braids are formed by the periodic motion of the legs as they pass through the swing and stance phases of the gait cycle. While the legs appear very close to each other in the XY plane, causing occlusion and interference, in the XT plane they are very clearly distinguishable. If these two patterns can be outlined separately in the slice, the two legs would be separated from one another throughout the video sequence.

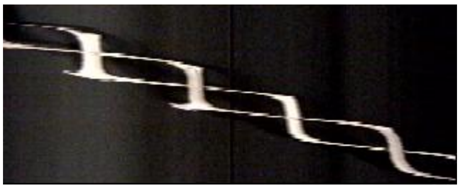


Figure 2: The periodic pattern of the legs in motion in a sample XT slice.

This outlining was achieved using an automatically initialised snaking algorithm. At the ankle height of the subject, an XT slice was obtained and an initial approximate of the snake was fit to the braided image. This initial template was then warped to follow the pattern's edges. Because of the similarity of the braided patterns at locally connected slices, this initial snake fitting was performed only once. After that, the snake fitting process was repeated at each slice from the ankle to the head of the subject and the result of the snake fitting from the previous height was used as the initialisation at the next. This resulted in a complete outline of the tracked region, which is held throughout the video sequence (see Figure 3).

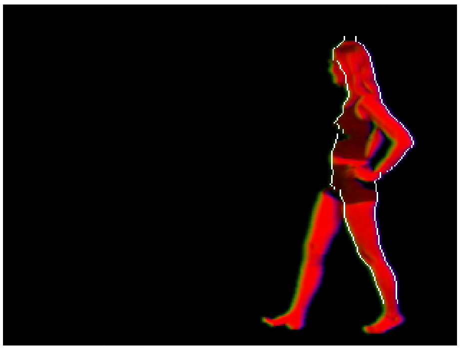


Figure 3: The outline of the area of interest in a sample frame.

2.2 Ellipse Fitting

Once the outline of the area being tracked has been obtained and the body has been segmented, the outline segments can be used as inputs for the ellipse-fitting algorithm. The outline obtained from the slice-by-slice snake algorithm is divided using the body segmentation into the tracked body parts: the head, torso, thigh and shank. Each of these segment outlines is passed to the ellipse-fitting algorithm and an ellipse is attached to each one independently.

So far, the body parts in each frame have been positioned independent of each other and independent of their locations in previous frames. However, this could cause anomalies in the results. In many human motion tracking algorithms, the segments are positioned subject to constraints and are dependent on the locations of their predecessor in the hierarchical tree structure of the body. This is a good way of avoiding unlikely positioning but it is prone to straying. Since each positioning is dependent on its own previous state and on the current state of its connected body parts, one bad fit would propagate through the image and through the image sequence causing the tracking to fail.

While our algorithm rarely suffers from straying and recovers quickly when it does, it can potentially result in nonsensical conclusions. Using our direct ellipse-fitting method, the result will be the best-fit ellipse with no limitations. This means that, while we can obtain a good estimate of the position and orientation of the body part, the size of the part may vary from frame to frame and the relative angles with other body parts could be unreasonable.

In order to overcome this problem, we apply constraints after the initial approximate fit has been acquired through direct ellipse fitting. Firstly, the dimensions of each ellipse are set to the average over the sequence. While there may be some change in the apparent dimensions as the person moves slightly toward or away from the camera or as muscles flex, it is reasonable to assume that the change will be insignificant. Next, the angles of the ellipses are temporally smoothed using a 1D Gaussian filter. This has an indistinguishable effect on the visual results but it ensures that the body parts are not rotating at unreasonable speeds from frame to frame and it improves the gait graphs. Lastly, the relative angles are checked to ensure that the joint angles are reasonable.

The final stage of the system design is the extraction of the gait data from the tracked body model. Because the ellipses contain information about the dimensions and orientations of the limb segments, the graph data for the thigh and shin angles can be extracted directly from the visual results. The flexion angles are the angles of the joints and so can be calculated as the difference of the body segment angles. A full set of sagittal view gait graphs along with a few significant gait parameters are presented here. The method used in implementing this system is described fully in [9].

3 RESULTS

3.1 System

The system was implemented on a PC with a 2.66GHz Pentium®4 processor with 1GB of RAM. The gait laboratory video images were filmed with an analogue video camera and were captured using an ATI All-in-Wonder®128 Pro video capture card. The natural-environment video images were filmed with a USB2.0 webcam. Some successful preliminary tests have been done using two synchronised USB2.0 webcams with a view to creating a fully integrated 3D system in the future. The program was implemented in Microsoft Visual C++ ® v6.0. The gait results were graphed in MATLAB®.

3.2 Input Data

The first video was filmed in a gait laboratory using a high quality camcorder and acquisition card. The subject is wearing fitted sportswear with her legs mostly bare and is walking without arm swing. The second video was filmed with a standard webcam in a normal environment, although the background is kept dark to ensure that the subject is clearly visible in contrast. The subject is dressed in everyday clothes and walking freely with arm swing.

In both video clips, the data was captured at 30 frames per second as a 320 x 240, 24-bit uncompressed RGB AVI. Higher resolution would give better results but would considerably slow the system. The sample video sequences used here are both approximately four seconds long (126 frames) totalling approximately 28MB. Processing time is less than one minute.

3.3 Visual Results

The visual data is useful for gauging the success of the algorithm and it could also be used to create an avatar to mimic the gait in a virtual 3D environment. This is a very tangible form of output but is only fully realisable with complete 3D gait data i.e. including the transverse and coronal planes of movement and including pelvis and ankle data. Here, we have concentrated on the sagittal plane and particularly on the main lower limb area (i.e. the thigh and shank), as this is the most challenging region in the acquisition of gait information.

Shown in Figure 4 are some sample frames from the two video sequences with the simple ellipse body model attached. Note the significant difference in picture quality and contrast between the two sequences yet despite this, there is little difference in the accuracy of the model fitting. However, because the leg is not directly visible in the second sequence, there is an unavoidable ambiguity with regard to the dimensions of the limb segments. In the graphical results, we plot the orientation of the segments throughout the sequence and so this ambiguity will not affect the gait measurements – another advantage of this ellipse-based method.

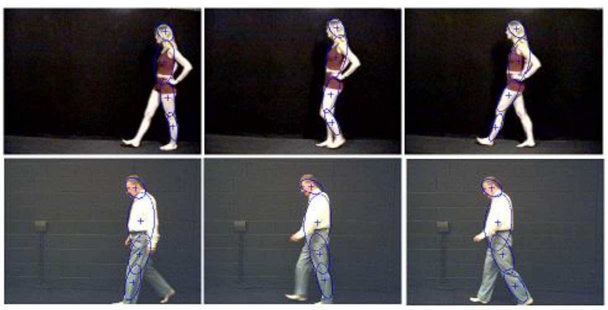
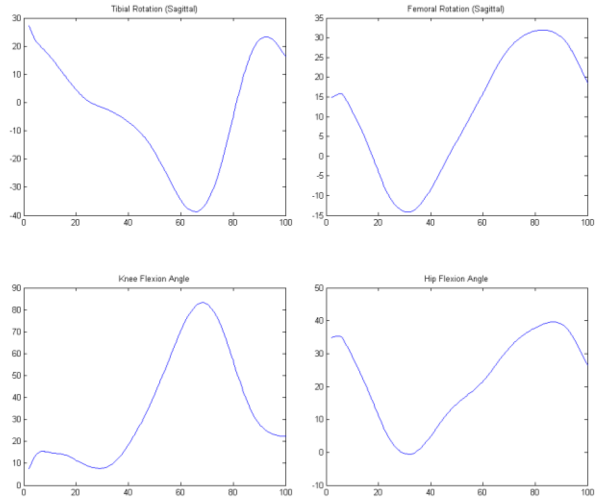


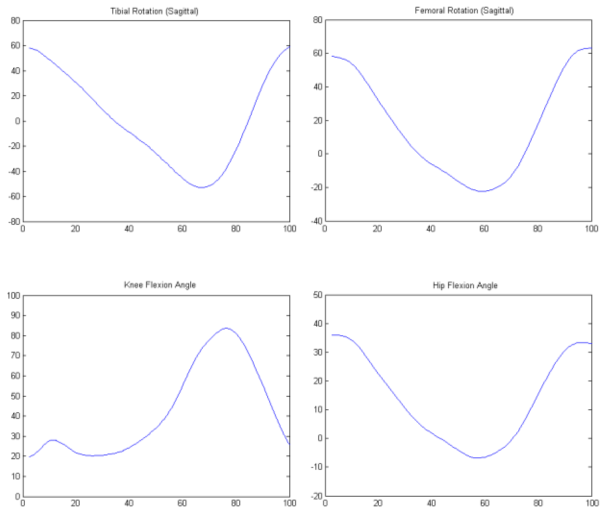
Figure 4: Sample frames from the gait laboratory video sequence and the natural-environment video sequence, showing the simple ellipse model attached to the images of the subjects.

3.4 Gait Data

As this system concentrates on the main lower limb sections, we have presented graphed data for the rotation and relative angles of the thigh and shank. These are typical gait graphs used in gait kinematics. The data in Figure 5 is presented from foot-strike (the point when the heel of the tracked leg strikes the ground) to foot-strike.



(a)



(b)

Figure 5: Gait data acquired from (a) the gait laboratory sequence and (b) the natural environment sequence.

Along with the visual and graphical results, a few significant gait parameters are normally acquired as part of full sagittal gait information. These are the walking velocity, the stride length and the cadence. The stride length is simply the length of two steps (the step length and walking velocity acquisition methods are described previously) and the cadence is the number of steps per minute. The values for the sample video sequences are presented below.

Table 1: Gait parameters for both video sequences

	Gait Laboratory Sequence	**Natural Environment Sequence**	**Units**
Subject's Height	175	180	cm
Walking Velocity	111	117	cm/sec
Stride Length	175	170	cm
Cadence	87	96	steps/min

4 DISCUSSION

Currently, there are few commercial marker-free systems in use in gait analysis. While marker-free systems are becoming more common in other areas such as sports science and animation, the accuracy and detail required for gait analysis makes this system design particularly challenging. In researching the current state of affairs, we discovered that the greatest obstacles in designing either marker-based or marker-free systems lie in sagittal-plane acquisition. This is also where the most information can be gleaned in diagnosing and analysing pathological gait. Thus, it was decided in this project to concentrate on designing a reliable marker-free system for monitoring sagittal-plane movement in the gait cycle.

We have achieved our outlined goals of building a completely automated, portable gait measurement system for use in sagittal-plane gait analysis. This system will allow patients' gait to be recorded in a relaxed and convenient environment without the need for a trained therapist to be present. Thus, the therapists can use their valuable expertise in diagnosing gait rather than spending their time mastering and using cumbersome marker systems. It is hoped that this system will be used by therapists and patients in the National Rehabilitation Hospital, Dublin where it was developed, and will perhaps become part of a more complete gait laboratory design in the future.

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