DEVELOPMENT OF AN OPTICAL MOTION ANALYSIS SYSTEM TO MEASURE SMALL MOVEMENT IN THREE-DIMENSIONAL SPACE

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ABSTRACT
Motion analysis techniques have been widely used in biomechanics for measuring large scale motions such as gait, but have not yet been significantly explored for measuring smaller movements such as the tooth displacements under load. In principle, very accurate measurements could be possible and this could provide a valuable tool in many engineering applications. The aim of this study was to investigate a novel method to measure small displacement in 3D space, as a step towards measuring tooth displacements to investigate the properties of the periodontal ligament. The characteristics of an optical motion analysis system have been evaluated using a wedge comparator with a resolution of 0.25μm to provide measured marker displacements in three orthogonal directions, for the diamond-shape and the spherical markers. The system accuracy, in the 20-200μm ranges, was ±1.17%, ±1.67% and ±1.31% for the diamond marker in x, y and z directions, while the system accuracy for the spherical marker was ±1.81%, ±2.37% and ±1.39%. The system repeatability measured under the different days, light intensity and temperatures for five times was ±1.7μm, ±2.3μm and ±1.9μm for the diamond marker, and ±2.6μm, ±3.9μm and ±1.9μm for the spherical marker in x, y and z directions, respectively. These results demonstrate that the system suffices accuracy for measuring tooth displacements and could potentially be useful in many other applications.

KEY WORDS
Optical motion analysis, Small movement, Measurement.

1. Introduction
Motion analysis techniques have been widely used in biomechanics for measuring movements. Previous investigators have focused on applications in the study of pose, gait and movements of the human body in a larger field of view (Capello et al 1997, Cappozzo et al 1996, Hunt et al., 2001, Green et al 1994, Higgins et al. 2003, Hirokawa et al. 2002, Holt. et al., 2000; Jones et al. 2001, Lopatenok et al., 2002;), Haggmann-Henrikson et al and Lundgren et al (1998) used the Qualisys Mac Reflex three-dimensional motion capture systems to measure deformations of dental implants under load. For measuring strain of soft tissue, Butler DL et al (1984) used a Milliken DBM4 high speed camera with 90mm zoomar lens and India ink marked on the specimens to measure strain inhomogeneity in tendon and fascia. Woo SL et al (1980) used specially designed instruments to measure the tendon cross-sectional area, and a video dimensional analyser system to measure accurately its “non-contact” tensile strain. There are many possible applications where smaller deformations occur, for example the measurement of deformations during material testing or testing of implant constructs, but these have not been widely explored. In principle, optical motion analysis systems could be capable of very accurate measurements, providing appropriate optics and calibration techniques were used, and there may be many applications in strain and deformation measurement in biomechanics and other areas of engineering.

The aim of the present project is to calculate the deformation of the periodontal ligament by measuring the relative displacements of the tooth under load. Periodontal ligament (PDL) is a soft tissue which connects between the root of tooth and alveolar bone. PDL consists of blood vessel and collagen fibres which embedded into alveolar bone to form a substantial part. The biological structure of PDL is very complicated. Until now, its mechanical properties still been investigated by researcher. Due to the specimen of PDL is easy dehydration and there are many considerable evidences which show that the deformation of PDL has a key influence on the tooth movement (Moxham and Berkovitz 1982, Parfitt 1960, Picton 1962, Will et al 1974), so to measure the tooth movement in 3D space, it is an approach to investigate the mechanical properties of PDL. For measuring tooth movement, two external marker clusters are attached on the teeth in order to measure rotation and translation of the tooth, using software developed by us based on previously developed for measuring knee and spinal movements (Holt et al 2000). However, apart from the manufacturer’s technical data which claims that the system resolution is equal to 1/60,000 of the field of view, the system accuracy and
repeatability have not been previously reported in the literature. In this study, our aim was to evaluate how accurately and repeatably the ProReflex-MCU120 Qualisys optical motion analysis system measures small displacements and to characterise the noise in the system. Specifically, we focused on the following questions: What is the actual resolution of the system in a small field of view? How accurately does the system measure small displacements in three orthogonal directions? How repeatable are the displacement measurements? What are the noise characteristics of the system? How is the system used to measure the tooth movement?

2. Method

The optical motion analysis system (Qualisys ProReflex-MCU120) includes infrared cameras, personal computer and software. For accurate measurement of a small field of view, the cameras lenses have a longer focal length than is normally used for gait analysis, so that the cameras can be positioned at a more convenient distance. The infrared cameras emit infrared radiation which is reflected back by the retroreflective markers, giving a high contrast between the markers and the background. 2-dimensional images of the markers, projected on the CCD of the cameras, are digitised and processed in real time by the signal processing circuit in the cameras. During data processing, the 2-dimensional coordinates of each marker’s centre are calculated and sent to the personal computer in real time via a serial computer interface. The system software, including linearization, calibration, models etc, displays and converts the marker’s 2D coordinates into 3D coordinates. This is normally done after the data has been captured. The maximum sampling frequency of the system is 120Hz.

The two cameras were placed as close as possible to the markers to maximise the system resolution (Fig.1). The distance (L) between the camera locations and the target was 69 cm, the cameras vertical angle was zero and horizontal convergence angel (A) was 78 degrees. An 68.18×51.14 mm overlapped field of view was created by two cameras. Two different types of markers were used in the experiments (spherical markers and elongated diamond markers). Spherical markers are conventional in the optical motion analysis system, as their profile remains the same when viewed from different directions. However, these are difficult to make in small sizes and are not needed unless substantial rotation of the markers occurs. Elongated diamond markers can potentially provide slightly better accuracy in the Qualisys system, as they take advantage of the different horizontal and vertical resolution of the CCD sensor.

The resolution and accuracy of the system were evaluated using an N.P.L. wedge type comparator that is a mechanical instrumentation (the function is similar with micrometer) with a resolution of 0.25µm as a standard. Two markers with size of diamond markers 2×4 mm and
spherical markers 2.5mm in diameter were attached to the moveable head of the comparator for measuring the displacement respectively. Two markers were moved along one axis and the displacement of two markers were detected by the infrared cameras. The comparator was rotated to measure along different axes. Two markers were moved in ten steps along each axis, and seven different step sizes were used (0.5µm, 1µm, 2µm, 3µm, 5µm, 10µm, and 20µm). The whole process was repeated five times on 5 days under the different light intensity and temperature. Every point was sampled for two seconds at a sampling rate of 60Hz, giving 120 frames of data for each point. The mean value of 120 frames was calculated as the value of one time measurement. This will reduce random error of the measurements due to ambient vibration. The actual measured step, its mean value, error, and percentage of actual measuring average step divided by ideal step were calculated. This percentage was used to evaluate the actual resolution of the system. The resolution was defined as the minimum step size that the system could detect.

The system accuracy was detected and calculated on a relative basis, using a comparator as a standard to produce a known displacement, and calculating the accuracy as a percentage of the measurement range. To compare the measurement accuracy with the different markers, the diamond markers and the spherical markers were tested alternately in the same experimental conditions, five times. The mean value, maximum error and minimum error were calculated for each point measured in each direction. The system accuracy was defined as the maximum absolute error in the range divided by the measurement range, expressed as a percentage.

Repeatability was evaluated by repeating the measurements of step up and step down in each direction for five times on different days, under different temperatures and light intensity. Standard deviation of the measurements was calculated as a measure of repeatability.

Random noise in the system was measured by sampling a static marker for 28800 frames over four minutes, repeated five times, and calculating the position of the marker in 3D space in each frame, its mean value and error. The errors expressed the system random noise, which includes ambient vibration, temperature drift and time drift in the signal processing circuit. Noise level was defined as the RMS amplitude (equal to one standard deviation σ) of the signal about the mean value, and the noise band was defined as 3.92σ. Assuming a normal distribution, the noise signal would be expected to lie in this band 95% of the time (the 95% confidence interval is ±1.96σ).

The relative measurement method is used to measure the tooth movement (Fig. 3). Two marker clusters were fixed on the measured tooth and the reference tooth through the brackets respectively. Under load, two marker clusters states were captured by the infrared cameras of the optical motion analysis system and the recorded data were transferred to the personal computer. The data processing software calculates the relative position changing of the measured marker cluster with reference marker cluster through the coordinate system transformation matrices and out of rotation and translation of 6 degrees of freedom.

![Fig. 3 The simulation model of measurement of tooth movement](image)

### 3. Results

The system resolution was found to be 10 µm in the 68.18×51.14 mm field of view. When the steps were 0.5, 1, 2, 3 and 5µm, the measured step as a percentage of the actual step divided by ideal step was less than 80% for each of the steps. For steps over 10µm, the system was found to be sensitive enough to repeatably measure the micro-displacement (Table 1). Note that this is the resolution of the whole system, not just the resolution of the cameras.

<table>
<thead>
<tr>
<th>Step Size (µm)</th>
<th>Diamond Marker</th>
<th>Spherical Marker</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>7.3 ± 1.5</td>
<td>31.2 ± 20.0</td>
</tr>
<tr>
<td>1</td>
<td>10.0 ± 3.0</td>
<td>21.1 ± 22.4</td>
</tr>
<tr>
<td>2</td>
<td>17.0 ± 3.7</td>
<td>22.0 ± 29.2</td>
</tr>
<tr>
<td>3</td>
<td>40.1 ± 6.5</td>
<td>47.4 ± 63.2</td>
</tr>
<tr>
<td>5</td>
<td>71.3 ± 89.7</td>
<td>74.3 ± 79.6</td>
</tr>
<tr>
<td>10</td>
<td>91.7 ± 94.5</td>
<td>91.4 ± 97.6</td>
</tr>
<tr>
<td>20</td>
<td>101.2 ± 110.5</td>
<td>103.3 ± 163.3</td>
</tr>
</tbody>
</table>

In the 20-200µm range, the system accuracy was found to be ±1.17%, ±1.67% and ±1.31% for the diamond markers, and ±1.81%, ±2.37% and ±1.39% for the sphere markers in x, y, and z directions, respectively. The
lowest accuracy was found in the y direction, for the spherical markers (Fig. 4).

Fig. 4  The system measurement accuracy (± %) in the 20-200µm ranges of x, y, z directions, for detected the diamond markers (dm) and the spherical markers (sm). The results were calculated with the percentage of maximum absolute error in the full range divided by the measurement range.

The repeatability defined as standard deviation, in the 20-200µm ranges, was found to be ± 1.7µm, ± 2.3µm and ± 1.9µm for the diamond markers, and ± 2.6µm, ± 3.9µm and ± 1.9µm for the sphere markers in x, y and z directions respectively.

The system random noise level (defined as the standard deviation, which is equal to the RMS amplitude) was 1.47µm. The noise band, defined as 3.92σ, was 5.76µm (Fig. 5).

Fig. 5  The system random noise. Here was shown one section of random noise (250 data).

In the system measurements, it was found that the diamond markers were slightly better than the sphere markers in terms of accuracy and repeatability.

4. Discussion and Conclusion

Unlike many engineering components, biomechanical structures typically occur in irregular shapes and undergo complex three-dimensional deformations on loading. There is thus a particular need for accurate, three-dimensional measurement of small movements in biomechanics. The characterisation of biological materials often requires more than the simple uni- or bi-directional measurements that are usually used for engineering materials. This study demonstrates that optical motion analysis could provide a valuable tool for these studies, and may have many other applications.

In this study, the system resolution, accuracy, and repeatability of the ProReflex-MCU120 Qualisys system was evaluated for measuring small displacements. In the 68.18 × 51.14 mm field of view, the system resolution was 10µm, which is higher than the theoretical value of 1/60,000 of the field of view (1.14µm) given by the manufacturer’s technical literature. This is because the theoretical calculation given by the manufacturer just considers the 16-bit resolution of the internal calculations in the camera, and ignores the system random noise. In fact, the influence of the system random noise has to be considered in the accurate measurement of small field of view. From Table 1, when the step size was 5µm or smaller, the system random noise resulted in lower sensitivity (less than 80%). The 10µm steps were the smallest that could be measured with a reasonable degree of accuracy, although much smaller movements could be detected. This different definition of the resolution accounts for the difference between this result and the manufacturer’s quoted resolution. Note that much of the loss of resolution was due to random noise, and that this may be reduced by appropriate digital filtering techniques. However, the 10µm resolution of the ProReflex-MCU120 system is sensitive enough for many biomechanical applications, including the measurement of tooth movement which is the aim of the present study. This resolution is equal to that of the LAS-5010 laser measurement system that has been applied in previous measurements of tooth movement (Hickman, 1997, Jones et al., 2001, Volp et al., 1996).

The system accuracy was evaluated separately in x, y, and z directions on a relative basis. The results suggested that the diamond marker had slightly better accuracy than the spherical marker in all three directions. The reason for this accuracy difference may be that the elliptic area surrounding the elongated diamond markers is slightly bigger than the circular area surrounding the spherical marker and the elliptic area provides more measurement points than the circular area. The larger the area of marker, the higher the accuracy of calculating central point of marker.

Repeatability was affected by the system random noise, and the reading error and hysteresis of the comparator. The repeatability and accuracy in the x and z directions were better than in the y direction. This may be because...
the y direction assumed in the measurement was the same as the main direction of ambient vibration, which produced the main part of the system random noise. Thus errors measured in the y direction were bigger than in x and z directions. Overall, our results demonstrated that the ProReflex-MCU120 Qualisys optical motion analysis system has sufficient accuracy for measuring small movement such as tooth displacement and could potentially be useful in many material deformation measurements in biomechanics and elsewhere.

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References


