Clinical gait evaluation of patients with knee osteoarthritis

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ABSTRACT

Knee osteoarthritis (KOA) is the most common osteoarthritis in lower limbs, and gait measurement is important to evaluate walking function of KOA patients before and after treatment. The third generation Intelligent Device for Energy Expenditure and Activity (IDEEA3) is a portable gait analysis system to evaluate gait. This study is to evaluate the accuracy and reliability of IDEEA3 for gait measurement of KOA patients. Meanwhile, gait differences between KOA patients and healthy subjects are examined. Twelve healthy volunteers were recruited for measurement comparison of gait cycle (GC), cadence, step length, velocity and step counts between a motion analysis system and a high-speed camera (GoPro Hero3). Twenty-three KOA patients were recruited for measurement comparison of KOA patients and healthy subjects are examined. Twelve healthy volunteers were recruited for measurement comparison of KOA gait patterns, while changes in knee kinematics, hip and ankle kinematics were important in discriminating between moderate and severe KOA gait patterns [5]. Elbaz et al. investigated the changes in gait patterns following the treatment with a novel biomechanical device, and revealed that the velocity, cadence and step length were improved after the treatment [6]. Juhl et al. reported that change in walking speed in patients with KOA is associated with self-reported disability [7]. Although patients’ ambulatory functions can be evaluated according to the range of normal gait parameters, reliable gait parameter measurements can give precise and valuable information for clinical diagnosis [8,9].

Application of gait analysis in musculoskeletal diseases has been proposed as a useful tool [10]. In clinical practice, gait is usually moderately...
evaluated using questionnaires, which produced subjective and pain-related functional assessments [4]. Pathological gait characteristics and quantitative gait analysis can be determined by gait laboratory methods such as optical motion tracking and analysis systems, video tape analysis, force plates and electromyography [11–14]. However, those methods have difficulties in clinical application, because of high cost, specific experimental space, technological requirements and tedious data analysis work. Most importantly, a few strides or limited data collected from a gait laboratory may not reflect true gait information of subjects. A portable, reliable, low-cost, and time-saving gait analysis system has been called for by clinicians and scientists. With the advancement of technology wearable sensors, such as small sizes of accelerometers and gyroscopes, make it possible to record and analyze gait outside conventional gait laboratories including the quantification of gait and movement disorders [11,15–19].

The Intelligent Device for Energy Expenditure and Activity (IDEEA, MiniSun, LLC, Fresno, CA, USA) is equipped with accelerometer and gyroscopes for monitoring physical activity and measuring gait parameters. The validity and reliability of IDEEA in measuring the spatial temporal gait variables in healthy people has been validated [20–22]. However, the reliability and validity of IDEEA in measurements of orthopedic patients is not always in consistency [13–15]. The third generation of IDEEA (IDEEA3) with wireless data communication has been improved for measurement of patients’ gaits. The object of this study was to evaluate the accuracy and reliability of IDEEA3 measurements for GC, cadence, step length, velocity and step counts in KOA patients.

2. Method

2.1. Participants

Twelve healthy participants (age: 28.4 ± 4.2y, BMI: 24.82 ± 3.10) and 23 KOA patients (age: 69.9 ± 6.6y, BMI: 26.56 ± 3.04) without lower limb problems were involved in this study. All patients were prepared for knee replacement surgery (the fourth phase of KOA). The hospitalized KOA patients participated in the experiment for measurement comparison between GoPro Hero3 and IDEEA3 to evaluate if IDEEA3 can be used for gait measurement in KOA patients effectively. This study was approved by the ethics committee of Capital Medical University. The proper informed consent was obtained before the experiment.

2.2. Devices

The three-dimensional digital optical motion analysis system was used for gait measurement with the sampling rate of 120frames/second. This system can measure movement non-invasively with extreme accuracy in real-time. In this study, six cameras were set to record volunteers’ movements. Nineteen markers were put on the subjects for measuring the lower extremity kinematics. One marker is placed on superior aspect at LS-sacral interface. Two other markers were placed on anterior superior iliac spines of both sides. Other twelve markers were placed on the following locations: medial/lateral malleolus and medial/lateral femoral condyle for both legs; the space between the second and third metatarsal heads of both feet; both heels. Four markers were placed on midtigh and midshank for both legs (Fig. 1).

IDEEA3 is a precious time based system consisting of sensors and recorders with larger data storage to monitor activity and to measure gait parameters. The seven tiny accelerometers/inclinometers (1.4*1.1*0.3 cm³) were fixed to skin by medical tape. The locations of sensors were placed as followed. One sensor was taped to the chest (4 cm below the jugular notch, vertical alignment). Two other sensors were taped to each thigh (mid-way between the anterior–superior iliac spine and patella, vertical alignment), other two sensors taped proximal to the ankles laterally, and another two sensors to the bottom of the feet (2 cm proximal to the head of the fourth metatarsal; horizontal alignment). All acquired data were downloaded to a computer for data analysis (Fig. 1).

The GoPro Hero3 is a portable shockproof camera, and has been reported useful for person instructional videos [23]. The GoPro Hero3 has the sampling rate of 60frames/second. It was attached to the participants using a custom-designed light frame behind the waist. When subjects walked on a carpet, the GoPro Hero3 recorded their trajectory of heel motion and the moment of initial contact of each foot, while gait cycles were simultaneously recorded by the motion analysis system (Fig. 1).

2.3. Experimental protocols

2.3.1. Experiment1: measurement comparison between the motion analysis system and GoPro Hero3

Although video tape analysis method has been widely used for gait analysis for decades, in order to ensure high accuracy of GoPro Hero3 measurement, we designed the experiment to compare GoPro Hero3 with the motion capture system that is considered as gold standard for gait measurement. The GoPro Hero3 was fixed to a rigid light stick, which was attached to the pelvis through a large soft patch (0.15m × 0.2m). The special-made carpet, made of high strength materials with low thermal expansion, was marked with precision grids (34 ± 1.0 mm/grid, total errors < 5 mm for the entire 20 meter length by three different rulers). Twenty meters are designed for test in this study, considering the patients’ walking ability and measurement environment of patients’ room. To ensure participants walking naturally at their usual paces, data from the first and last 2 m of the testing session were not used according to conventions set by Perry [24], leaving 16 m meters of walking for gait analysis. The variation trends of data were checked to guarantee the synchronization (Fig. 1).

Initial contact moment of each participant’s walking was analyzed by video tape replay method with software GoPro studio (GoPro, Inc., San Mateo, CA, USA). In addition, step length in the video was determined by heel’s exact locations on the carpet grid during foot-ground contact (accuracy to 3 mm based on the number of 34 mm grids between steps and the locations within the grid on the video). The accuracy is about 2 pixels on the frame, reflecting to less than 0.002 m error in displacement. GC from video was determined by precise time period between initial contacts of the same foot; cadence was the inverse of time period between adjacent initial contacts; and velocity was obtained from dividing the GC by the stride length.

2.3.2. Experiment2: measurement comparison between GoPro Hero3 and IDEEA3

The experiments were conducted in bright environment with low noise and no visual distraction to ensure the patients’ safety, because their ages were 69.9 ± 6.6y. Participants wore comfortable clothing and flat shoes, following the recommendations by Kressig et al. [25], that measurements should be performed in a well-lit, quiet environment and the clothing of participants should be comfortable with their appropriate types of footwear with heel height not exceeding 3 cm. All participants walked on a marked carpet (20 × 1.5 m in length) in their comfortable way in the hospital corridor, wearing IDEEA3 with GoPro Hero3 tied behind their pelvis (Fig. 1). For consistency, the same individual placed sensors and markers for all trials and participants.

2.4. Statistical Analysis

The measurements from GoPro Hero3 and motion analysis system were compared using paired t-test to examine the differences. The Concordance Correlation Coefficient (CCC) and Intraclass Correlation
Coefficient (ICC) were used to estimate the consistency of the two measurements. ICC model select two-way mixed effects model where people effects are random and measurement effects are fixed [26]. Meanwhile, paired t-test was used to compare the measurements from IDEEA3 and GoPro Hero3 in KOA patients. The ICC, CCC, Bland-Altman plot and scatter plot were used to estimate the consistency of IDEEA3 measurements and GoPro Hero3 measurements (Fig. 2).

The errors were calculated to describe the deviations of two measurements. The error for each parameter of each subject is defined as:

$$\text{Error}(\%) = \frac{\sum \text{Motion results} - \text{GoPro results}}{\sum \text{Motion results}} \times 100\%$$

$$\text{Error}(\%) = \frac{\sum \text{GoPro results} - \text{IDEEA results}}{\sum \text{GoPro results}} \times 100\%$$

The average error of each parameter in this study is obtained by the average of errors derived from above equations. The independent t-test was used to compare the gait differences between KOA patients and healthy subjects. The SPSS Version 21.0 (SPSS, Inc., Chicago, IL, USA) statistical package was used for statistical analysis. Statistical significance is defined as p < 0.05.

### 3. Results

The results of motion analysis system and GoPro Hero3 in healthy subjects at natural speed with flat shoes were 1.121 ± 0.071 s and 1.119 ± 0.066 s for GC, 107.626 ± 7.102 steps/min and 107.573 ± 6.524 steps/min for cadence, 0.646 ± 0.0534 m and 0.646 ± 0.0528 m for step length and 1.160 ± 0.106 m/s and 1.161 ± 0.100 m/s for velocity. The step counts for the two measurements were both 11.160 ± 1.200 with flat shoes. All ratios of GoPro Hero3 results to motion analysis system results were around 1.0 (Table 1). The average errors(%) of the two measurements were showed in Fig. 3.

The results of IDEEA3 and GoPro Hero3 in KOA patients were 1.239 ± 0.128 s and 1.239 ± 0.133 s for GC, 98.438 ± 9.305 steps/min and 98.390 ± 9.672 steps/min for cadence, 0.439 ± 0.076 m and 0.440 ± 0.078 m for step length and 0.727 ± 0.163 m/s and 0.727 ± 0.164 m/s for velocity. The step counts for the two measurements were both 80.174 ± 27.905. All ratios of IDEEA3 results to GoPro Hero3 results were around 1.0 (Table 1). The average error(%) of IDEEA3 measurement compared with those from GoPro Hero3 measurement in GC, cadence, step length and velocity were 0.515%, 0.432%, 3.177% and 3.316% respectively (Fig. 3).

All p-values of paired t-test for GC, cadence, step length and velocity were greater than 0.05, while CCC and ICC results were all above 0.95 (Tables 1–2). Bland–Altman plots showed that 95.65%, 95.65%, 93.8% and 95.65% of the KOA patients were within the 95% confidence interval of the agreement limit for the four parameters (Table 2). Scatter plots showed in Fig. 3. All measurement comparison for step counts were 100% (Table 2).

The p-values of independent t-test results for GC, cadence, step length and velocity between the healthy subjects and KOA patients were 0.006, 0.006, 0.001 and 0.001 at natural speed.

### 4. Discussion

As motion analysis system has long been regarded as a reliable gait measurement method [2,27], results from this study have shown that measurements of GoPro Hero3 and measurements of IDEEA3 for GC, cadence, step length, velocity and step counts of KOA patients are reliable.
Fig. 2. Scatter plots of the Motion Analysis measurement results and GoPro Hero3 measurement results. The dotted line represents the identity line: $y = x$. Figure (a) and figure (b) are scatters of cadence and velocity results of healthy subject results. Figure (c) and figure (d) are scatters of cadence and velocity results of KOA patients. The figure of cycle results is close to cadence results, and the figure of step length result is close to the velocity results.

Table 1
Paired t-test results/CCC/ICC results of high-speed camera measurement (GoPro Hero3) and motion capture system in healthy subjects with flat shoes.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>High-speed Camera Results (a)</th>
<th>Motion Capture System Results (b)</th>
<th>Ratio (a/b)</th>
<th>T-test (p Value)</th>
<th>CCC (r value)</th>
<th>ICC (r value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gait cycle</td>
<td>$0.913 \pm 0.061$</td>
<td>$0.916 \pm 0.065$</td>
<td>0.997</td>
<td>0.463</td>
<td>0.977</td>
<td>0.988*</td>
</tr>
<tr>
<td>cadence</td>
<td>$131.991 \pm 9.243$</td>
<td>$131.625 \pm 9.748$</td>
<td>0.999</td>
<td>0.529</td>
<td>0.980*</td>
<td>0.990*</td>
</tr>
<tr>
<td>step-length</td>
<td>$0.805 \pm 0.086$</td>
<td>$0.806 \pm 0.085$</td>
<td>0.999</td>
<td>0.567</td>
<td>0.999*</td>
<td>0.999*</td>
</tr>
<tr>
<td>velocity</td>
<td>$1.783 \pm 0.274$</td>
<td>$1.776 \pm 0.275$</td>
<td>1.004</td>
<td>0.285</td>
<td>0.996*</td>
<td>0.996*</td>
</tr>
<tr>
<td>Normal Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gait cycle</td>
<td>$1.119 \pm 0.066$</td>
<td>$1.121 \pm 0.071$</td>
<td>0.998</td>
<td>0.401</td>
<td>0.996*</td>
<td>0.997*</td>
</tr>
<tr>
<td>cadence</td>
<td>$107.573 \pm 6.524$</td>
<td>$107.626 \pm 7.102$</td>
<td>0.999</td>
<td>0.836</td>
<td>0.996*</td>
<td>0.996*</td>
</tr>
<tr>
<td>step-length</td>
<td>$0.646 \pm 0.0528$</td>
<td>$0.646 \pm 0.0534$</td>
<td>1.000</td>
<td>0.626</td>
<td>0.997</td>
<td>0.998*</td>
</tr>
<tr>
<td>velocity</td>
<td>$1.161 \pm 0.100$</td>
<td>$1.160 \pm 0.106$</td>
<td>1.001</td>
<td>0.498</td>
<td>0.996*</td>
<td>0.997*</td>
</tr>
<tr>
<td>Slow Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gait cycle</td>
<td>$1.306 \pm 0.131$</td>
<td>$1.304 \pm 0.133$</td>
<td>1.002</td>
<td>0.495</td>
<td>0.998*</td>
<td>0.998*</td>
</tr>
<tr>
<td>cadence</td>
<td>$92.727 \pm 9.002$</td>
<td>$92.865 \pm 9.233$</td>
<td>0.999</td>
<td>0.539</td>
<td>0.998*</td>
<td>0.998*</td>
</tr>
<tr>
<td>step-length</td>
<td>$0.574 \pm 0.087$</td>
<td>$0.572 \pm 0.082$</td>
<td>1.003</td>
<td>0.286</td>
<td>0.999*</td>
<td>0.999*</td>
</tr>
<tr>
<td>velocity</td>
<td>$0.887 \pm 0.148$</td>
<td>$0.886 \pm 0.148$</td>
<td>1.001</td>
<td>0.745</td>
<td>0.999*</td>
<td>0.999*</td>
</tr>
</tbody>
</table>

Units in Table 1: use second for cycle, steps/min for cadence, meter for step-length, and m/s for velocity.

* $p = 0.0001$. 

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In Bohannon’s study [8], the comfortable speed was 1.39 ± 16.4 m/s for healthy subjects in age 20 s with mean speed of 0.82 after height normalization, and the comfortable speed was 1.33 ± 20.9 m/s for healthy subjects in age 60 s with mean speed of 0.8 after height normalization. Astephen et al. [5] reported that the comfortable speeds of healthy subjects in age 70 s were 1.36 ± 0.19 m/s (0.80 speed/height) that they are consistent with Bohannon’s results. However, according to Huang’s study [28], the comfortable speeds of healthy subjects in age 60 s were 0.89 ± 0.32 m/s (0.59 speed/height), and the comfortable speeds for healthy subjects in age 20 s in our study were 1.16 ± 0.10 m/s (0.69 speed/height). One possible reason for the differences between studies might be the race differences, because the subjects are westerners in Bohannon’s and Astephen’s studies while the subjects are Asians in our and Huang’s studies. Another possible reason is individual differences for understanding and controlling of the comfortable speeds.

Astephen et al. reported the speeds of severe KOA patients (the third and fourth phase of KOA) are 0.92 ± 0.24 m/s (0.55 speed/height) [5]. According to Huang, the mean speeds of severe KOA patients (the third and fourth phase of KOA) are 0.83 ± 0.18 m/s (0.53 speed/height) [28]. The speeds for KOA group (the fourth phase of KOA) in our study are 0.73 ± 0.16 m/s (0.45 speed/height), which are lower than Astephen’s and Huang’s results. The possible reason is the phase differences of KOA because patients of our study were much more severe than patients in Astephen’s and Huang’s studies, which may indicate that gait is affected largely by severity of KOA.

The independent t-test results between healthy subjects and KOA patients in this study showed that all p-values of GC, cadence, step length and velocity are below 0.05. The KOA patients would walk with longer GC, lower cadence, shorter step length and slower speed compared with healthy subjects, which are consistent with Astephen’s and Huang’s study.

Backhouse’s validation study [13] of IDEEA2 have shown reliable results for step counts in 12 healthy subjects but unreliable results for Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>IDEEA Results (a)</th>
<th>GoPro Results (b)</th>
<th>Ratio (a/b)</th>
<th>T-test (p Value)</th>
<th>CCC (r value)</th>
<th>ICC (r value)</th>
<th>B-A Plot results</th>
</tr>
</thead>
<tbody>
<tr>
<td>gait cycle</td>
<td>1.239 ± 0.128</td>
<td>1.239 ± 0.133</td>
<td>1.000</td>
<td>0.928</td>
<td>0.992</td>
<td>0.996</td>
<td>95.65%</td>
</tr>
<tr>
<td>cadence</td>
<td>98.438 ± 9.305</td>
<td>98.390 ± 9.672</td>
<td>1.001</td>
<td>0.810</td>
<td>0.996</td>
<td>0.997</td>
<td>95.65%</td>
</tr>
<tr>
<td>step-length</td>
<td>0.439 ± 0.076</td>
<td>0.440 ± 0.078</td>
<td>0.998</td>
<td>0.899</td>
<td>0.972</td>
<td>0.986</td>
<td>93.80%</td>
</tr>
<tr>
<td>velocity</td>
<td>0.727 ± 0.163</td>
<td>0.727 ± 0.164</td>
<td>1.000</td>
<td>0.965</td>
<td>0.982</td>
<td>0.993</td>
<td>95.65%</td>
</tr>
<tr>
<td>step counts</td>
<td>80.174 ± 27.905</td>
<td>80.174 ± 27.905</td>
<td>1.000</td>
<td>–</td>
<td>1.000</td>
<td>1.000</td>
<td>100%</td>
</tr>
</tbody>
</table>

Units in Table 2: use second for gait cycle, steps/min for cadence, meter for step-length, and m/s for velocity.

‘* p = 0.0001.'
stride length, speed and step counts in 12 rheumatoid arthritis patients. There is correlation relationship of Bland-Altman plot between IDEEA2 measurements and GAITRite measurements, which implies that measurements by IDEEA2 were not consistent with measurements by GAITRite in rheumatoid arthritis patients. However, in our study IDEEA3 measurements for GC, cadence, step length, velocity and step counts are consistent with GoPro Hero3 measurements in 23 KOA patients, and no correlation was found in the Bland–Altman plots between IDEEA3 measurements and GoPro Hero3 measurements. A number of reasons could arise for the different results. First, IDEEA3 works better for gait measurement of patients than IDEEA2. Second, the differences of experimental protocols might cause different results. Application of IDEEA (both IDEEA2 and IDEEA3) is assumed under normal daily activity conditions when subjects usually wear shoes. Patients in our study wearing flat shoes followed guidelines by Kressig et al. [24] while patients in Backhouse’s study wore soft socks during tests. In addition, patients in Backhouse’s study are different from those in our study. There are some limitations in this study. Given the limited record space of motion analysis system, it is feasible to evaluate the accuracy and reliability of IDEEA3 by the comparison with GoPro Hero3. GC, cadence, step length, velocity and step counts- examined in this study are essential to clinically evaluate KOA patients’ gaits. However, in the future more gait parameters such as knee angles etc. and more patients with different orthopedic problems should be included for better gait assessment. The age-paired normal subjects would also be included in future studies.

5. Conclusion

The measurements of GC, cadence, step length and velocity by motion analysis system are consistent with the measurements by GoPro Hero3 in healthy individuals. The measurements of GC, cadence, step length, velocity and step counts by GoPro Hero3 are not statistically different from the measurements by IDEEA3 in KOA patients. IDEEA3 can be effectively used for the measurements of GC, cadence, step length, velocity and step counts in KOA patients. The KOA patients walk with longer GC, lower cadence, shorter step length and slower speed compared with healthy subjects in natural speed with plat shoes.

Conflicts of interest

There is no financial or personal relationship to disclose, nor any other conflicts of interest, that may bias or influence this study.

Authorship Declaration

All authors listed meet the authorship criteria according to the latest guidelines of the International Committee of Medical Journal Editors; all authors are in agreement with the manuscript.

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References