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Evaluation of the ShapeTape for studying biomechanics in the workplace

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Abstract— **Motion capture systems may be difficult to use in harsh environments such as a poultry plant, and therefore should be self-contained, portable, unobtrusive, and not interfere with or be degraded by plant machinery or processes. The purpose of this study was to evaluate the validity, reliability and accuracy of the ShapeTape system as a potential solution. This was accomplished by comparing kinematic data from the ShapeTape against the Vicon system. Subjects performed cyclical movements along a plane angled 45° up from the horizontal using their right arms. Results revealed that the ShapeTape kinematic data was significantly larger than the Vicon data, yet statistically reliable.**

I. Introduction

Deboners have been shown to be able to remove poultry breast meat at a line speed of up to 40 birds/minute that have resulted in 10,000 cuts per day per individual [1]. This highly repetitive task may have contributed to the development of musculoskeletal disorders in this population and has remained a concern for the industry [2]-[4]. Studies on repetitive arm movement have usually been conducted under ideal laboratory conditions where the environmental factors were controlled [4][5]. However, collecting kinematic data throughout an individual's entire work day while in the work environment could address a series of questions that would not be possible to ascertain in the laboratory environment [6]. This may include studying job rotation, fatigue and other work environment factors that are difficult to simulate in the laboratory environment. There are various tools that may be used to conduct these studies; however, each has benefits and drawbacks when it comes to being an objective, effective and quantitative measure that may be used repeatedly.

Ergonomists have used an array of qualitative tools such as checklists and surveys to evaluate human performance in the work environment [7]-[9]. Research has shown that these qualitative tools may not correlate to quantitative measurements and may often be subjective [10][11]. Therefore, it would be beneficial to combine qualitative and quantitative tools in order to objectively assess a workers performance. There are a variety of motion capture systems available that may be used to quantify the biomechanics of the task. This study examined one such device, the ShapeTape system by Measurand Inc. that is an appealing solution because it is portable, unobtrusive and does not interfere with or degraded by plant machinery or process.

The ShapeTape system consists of multiple looped bend enhanced optical fibers that when bent experience a linear loss of light intensity that corresponds with curvature [13]-[15]. The ShapeTape system has been used in various applications with varying levels of accuracy to measure angular data [16]-[20]. Morin and Reid [18] found that the ShapeTape consistently measured larger-than-actual angles. Also, the accuracy of the ShapeTape appears to be dependent on its length, because the position error accumulates as the signal is integrated over distance [21]. These studies examined the ShapeTape under ideal conditions when it was not being worn by a human subject. Therefore, it is unclear whether these errors would be consistent with and similar to when the ShapeTape system is worn by a human subject.

The purpose of this study was to evaluate the effectiveness of the ShapeTape system while being worn by a human subject and compare it to the Vicon system. The Vicon system has been demonstrated to have an overall accuracy of 63±5μm and precision of 15μm [22] and is commonly used to study upper extremity biomechanics [5], [23]-[26]. Both systems were worn at the same time by human subjects who performed an upper extremity movement that simulated a poultry deboning task. The hypothesis was that the ShapeTape system would consistently measure larger angles compared to that of the Vicon system. The significance of this study is that by understanding the ability of the ShapeTape system to measure biomechanics, may aid in the interpretation and evaluation of any future studies that may use this system.

II. Methods

A. Subjects

Ten subjects (6 males, 4 females, age 33.8±11.2 years) participated in this study and had no known neuromuscular disorders. Informed consent was obtained prior to the study. The study was approved by the Georgia Institute of Technology Institutional Review Board.

B. Equipment

The ShapeTape system consists of a fiber optic tape and two gyroscopes (Fig. 1.a). The 139cm long ShapeTape attaches along the length of the arm. The ShapeTape is able

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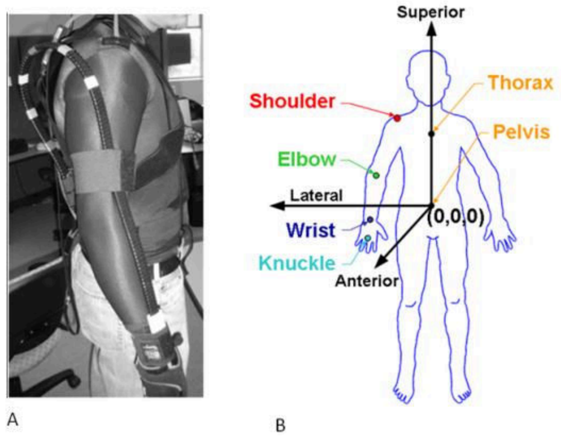

Figure 1. The ShapeTape (a) instrumented for the right arm and (b) coordinate frame.

to determine the Cartesian coordinates (x, y and z) of the endpoint of the tape, which corresponds to the subject's right dorsal metacarpal III (knuckle). As the arm moves the ShapeTape will bend and twist. This causes a linear loss of light intensity at points along the ShapeTape that corresponds to the pose of the ShapeTape and is used to calculate changes in angular and endpoint displacements. Two gyroscope modules are placed over the spinal cord, one at L4-5 (Pelvis, Fig. 1.b) and the other at T5-7 (Thorax, Fig. 1.b). The anthropometrics of the subject is used to calculate the kinematic variables from the raw ShapeTape data. The data output for the ShapeTape, includes all pertinent endpoint Cartesian coordinate data (x, y and z) with the origin being at the pelvis.

The Vicon system consists of 6 MCam2 video cameras with infrared strobes (623nm) and digital CMOS sensors (resolution 1280x1024 pixels). The Vicon system was calibrated to an accuracy mean residual of 1.034±0.391mm. Ten reflective markers were placed on the upper body, eight on the arm and two directly on the ShapeTape gyroscopes. The ShapeTape data was translated into the Vicon coordinate frame, and the systems were synchronized using the same 5V pulse trigger signal.

C. Task Protocol

Subjects held the rotary device (Fig. 2.a) that consisted of a bike crank and pedal (0.35m diameter) placed at 45° angle up from the horizontal plane. The subject stood in front of the rotary device that was placed at a fixed height of 29 inches. A cycle was defined as a single rotation, beginning and ending at the starting position, with the arm fully extended at the top of the bike crank. This motion simulated a poultry deboning task. Subjects completed 35 cycles in the clockwise and counter clockwise directions at three speeds indicated by an audible metronome: 60 cycles/min (fast), 20 cycles/min (medium) and 15 cycles/min (slow). A five minute rest period was observed after each speed.

D. Performance variables

Three performance variables were calculated using the ShapeTape and Vicon kinematic data (Fig. 3): (1) travelled knuckle distance, (2) hip knuckle distance, and (3) elbow

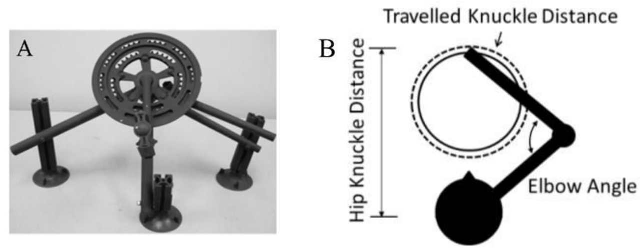

Figure 2. (a) The rotary device viewed from the front. (b) Performance variables.

angle. The travelled knuckle distance, was the distance that the knuckle travelled along the circular path. The hip knuckle distance, was the distance between the knuckle and the pelvis location. The elbow angle was defined as the inclusive elbow angle of the right arm.

E. Data Analysis

The ShapeTape data were filtered at a sampling rate of 100 Hz due to equipment constraints, whereas the Vicon data were filtered at 120 Hz so as to adequately match the synchronized ShapeTape data to the Vicon data through linear interpolation. The Start of a cycle was calculated as the point at which the knuckle reached a local maximum vertical displacement. The ShapeTape data were detrended with a linear function across every subject, speed and direction in order to account for inherent drift associated with the fiber optic tape sensor. Each cycle was normalized to its duration and then sampled at 1% increment of the cycle. Outliers were removed if within a cycle the data were outside of the three standard deviation control limit; then the data for both the ShapeTape and Vicon were removed for that particular cycle.

In order to compare the ShapeTape against the Vicon system, the performance variables were calculated and evaluated at 1% cycle intervals (i). The following equations were used for each performance variable in order to compare between the systems, and will be referred to as the comparative variables:

1. Comparative Variable *TKD*: The *travelled knuckle distance* performance variable was evaluated by taking its ratio as measured by the Vicon system (δV_i) and the ShapeTape system (δST_i).

$$TKD = \text{mean}\left(\frac{\delta V_i}{\delta ST_i} - 1\right) * 100 \qquad (1)$$

2. Comparative Variable *HKD* and *ELB*: The *hip knuckle distance* and *elbow angle* performance variables were evaluated by calculating the root mean squared difference between the Vicon system (δV_i) and the ShapeTape system (δST_i).

$$\sqrt{\frac{\sum_{i=1}^{n}(dV_i - dST_i)^2}{n}} \qquad (2)$$

The validity was measured by the accuracy of the instrument on the three performance variable across different speeds. Repeated measures one-way ANOVA's were run on the results of the comparisons of the performance variables between the systems (Equation 1 and 2) with speed as the independent variable. Post-hoc Tukey's HSD tests were

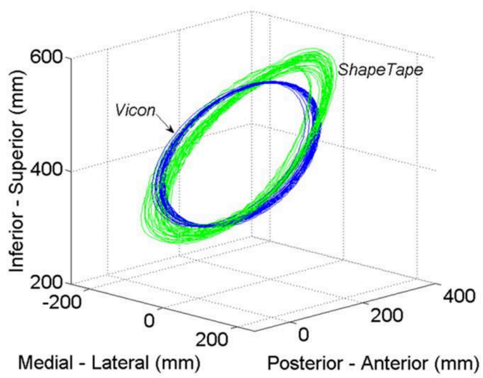

Figure 3. Raw ShapeTape knuckle data transposed onto the Vicon coordinate frame for one subject.

conducted where applicable. The degree of consistency between the ShapeTape and the Vicon was measured by equivalent-instruments reliability; in this case, the Pearson correlation for each performance variable was evaluated.

III. Results

A one-way ANOVA was used to test the differences among different speeds of the *travelled knuckle distance* comparative variable (TKD). There was a significant difference of TKD across speeds, $F(2,4895) = 10.88, p < 0.01$ with $R^2 = 46.6\%$. A post-hoc Tukey's HSD showed that TKD did not differ between slow and medium speeds, but TKD at both of these speeds differed with the fast speed, $p < 0.01$. TKD is not the same across subjects, which may be due to anthropometric differences in subjects with regards to how well the ShapeTape system fits onto the subject. Figure 3 shows the raw ShapeTape and Vicon data for the *travelled knuckle distance* in both the clockwise and counter-clockwise directions for the medium speed of one subject. The results demonstrate that the ShapeTape trajectories are consistently larger than the Vicon trajectories. An independent samples t-test was done on the TKD comparative variable to account for direction. This resulted in no significant difference between clockwise (1.995 ± 0.333) and counter-clockwise (2.015 ± 0.294) directions, $t(196) = 0.46, p = 0.643$.

A one-way ANOVA was used to test the differences between the ShapeTape and Vicon *hip knuckle distance* (HKD) performance variable comparison (Eq. 2). There was significant difference of *HKD* across speeds, $F(2,4895) = 10.88, p < 0.01$ with $R^2 = 46.6\%$. A post-hoc Tukey's HSD showed that *HKD* did not differ between fast and medium speeds, but *HKD* at both these speeds differed with the slow speed, $p < 0.01$.

A one-way ANOVA was used to test the differences between the ShapeTape and Vicon *elbow angle* (ELB) performance variable comparison (Eq. 2). There was significant difference of ELB across speeds, $F(2,445.2) = 42.25, p < 0.01$ with $R^2 = 39.7\%$. A post-hoc Tukey's HSD showed that *ELB* differed across speeds, $p < 0.01$.

The Pearson correlations for each performance variable were statistically significant and showed varying degrees of validity and reliability between systems across the three speeds (Table 1). For the *travelled knuckle distance* performance variable, the ShapeTape data was consistently greater than the Vicon data and had low reliability. At the fast speed there was no significant difference in reliability between the systems. The *hip knuckle displacement* and the *elbow angle* performance variables validity shown in Table 1 revealed that the ShapeTape reported larger values than the Vicon.

Table 1. Summarized validity and reliability for each of the response variables.

Variable	Speed	Validity		Reliability
		Mean±Std	95% CI	
TKD (%)	S	-5.99±19.26	-7.56,-4.42	0.37*
	M	-7.57±18.94	-9.09,-6.06	0.35*
	F	-2.67±20.95	-5.02,-0.32	0.08
HKD (mm)	S	47.9±42.2	44.05,51.72	0.85*
	M	61.9±55.2	56.91,66.96	0.66*
	F	47.9±40.1	42.51,53.33	0.71*
ELB (°)	S	9.2±5.1	8.77,9.71	0.79*
	M	10.4±6.34	9.88,11.03	0.60*
	F	10.0±5.0	9.31,10.68	0.68*

IV. Discussion

The purpose of this study was to evaluate the effectiveness of the ShapeTape system while being worn by a human subject and compare it to a commonly accepted motion capturing system, such as Vicon. The results of this study supported the hypotheses that the ShapeTape kinematic data was consistently greater than the kinematic data obtained from the Vicon system across all speeds. Therefore, the ShapeTape is not suited for fine motion capture tasks that require measurements to be accurate within 1 mm or 1°, instead it is adequate for gross movements. The movement errors observed in the current study were similar to what has been reported in other studies when the ShapeTape was measured under idealized conditions [15]-[21].

There are a few confounding factors that may have influenced the degree to which the ShapeTape kinematic data was larger than the Vicon data. The rotary device was secured to a non-adjustable height table in order to emulate conditions in a poultry plant. The lack of height adjustment on the rotary device could have resulted in different initial arm postures across subjects. This combined with the different subject anthropometrics could have led to some variation in the initial amount of the ShapeTape twist and bending resulting in large position errors observed between the ShapeTape and Vicon systems. These position errors concur with Morin and Reid (2002) and are likely due to error accumulation in the signal when integrated over time. Danish *et al.* modeled the optical characteristics of a ShapeTape fiber optic sensor and determined that drift and hysteresis can contribute to errors in accuracy [14]. The ShapeTape operates on the principle of integrating the light over the length of the fiber, and therefore it is reasonable to expect that short and rigidly attached fibers will lead to smaller errors. Therefore, the type of ShapeTape error observed in this study was reasonable given the nature of the task and the difficulty of attaching the 139cm ShapeTape rigidly to the arm.

Morin and Reid (2002) demonstrated that the ShapeTape angles are consistently larger when compared to the OptoTrak [18]. The ShapeTape was rigidly attached to the OptoTrak and not subjected to human anthropometrics, so it was anticipated that our resulting errors would be greater. Since it was not possible to rigidly attach the ShapeTape to the subjects arm, there is some inherent bend and twist in the optic fiber tape that resulted in larger errors than when compared to ideal conditions. Baillot et al. had similar findings where the angular errors were greater than the expected positions by up to 10° due to bending in the tape [20]. Even though the experimental setup was different, these results corroborate what was demonstrated in the current study.

Therefore, it is proposed that the reason why the ShapeTape errors may be larger than expected is because in the current study the optic fiber could not be rigidly attached to the subjects arm. In addition, the experiment was not conducted with ideal conditions, but instead was a test to determine how different subject anthropometrics would influence the results. The recommendations for using the ShapeTape in the field would be to ensure that the optic fiber cables are position similarly across subjects, and to attach the optic fiber cable as rigidly as possible while still allowing movement.

V. Conclusion

The kinematic data obtained from the ShapeTape is consistently larger than that obtained from the Vicon. Therefore, the ShapeTape is less accurate yet adequate for evaluating the gross movement of the upper arm.

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