The Validation of Measurand Shape Tape for Measuring Joint Angles

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ABSTRACT

Shape Tape is a light weight, flexible ribbon that detects bend and twist along its length, thereby following its own position in 3D space. In this study, the ability of Shape Tape to accurately report joint angles was investigated by validating Shape Tape against an OptoTrak position sensing system. The ultimate goal is to use Shape Tape in a wearable system to measure joint angles in subjects in the field.

INTRODUCTION

Canadian military personnel undergo physiological and biomechanical stresses during combat training and in operational settings. A means of quantifying the operational effectiveness of these personnel in the field is desired. In order to do so, a portable system to measure and record relevant biomechanical and physiological parameters is under development [1].

One important aspect of biomechanical assessment is the kinematic analysis of limb motion in space. Kinematics describes the positions and orientations of the limb, as well as the corresponding angular velocities and accelerations. In a laboratory setting, patient or subject motion is usually tracked using externally referenced motion analysis systems. These systems involve equipping the limb under study with an array of markers on appropriate landmarks and videotaping the subject as s/he performs a specific task or tasks. Such systems are necessarily confined to an indoor setting and spatially limited movements. Internally referenced motion analysis systems involve the use of sensors with self-motion sensing capabilities, such as accelerometers or gyroscopes. These systems operate regardless of external reference points, however, position errors in these devices accumulate as the sensor signal and associated errors are integrated over time.

A promising measurement device for tracking limb position in space is Shape Tape™, manufactured by Measurand[1]. In this study, the ability of Shape Tape to accurately and repeatably measure a static joint angle and track a time-varying joint angle was investigated.

SHAPE TAPE™ OPERATION

Shape Tape is based on paired fibre optic sensing loops which are placed at regular intervals along a metal substrate [2]. These loops detect bend and twist along the substrate and the resulting signals are converted into orthogonal orientation vectors, **U**, **N** and **B**, for each sensor. In this way, Shape Tape tracks the position of each sensor along the tape, relative to a base or reference point (see Figure 1).

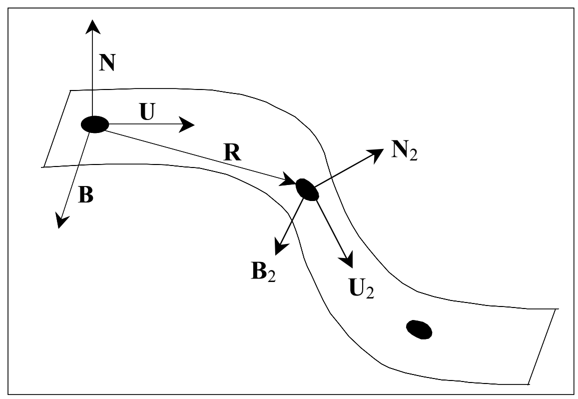

Figure 1: Shape Tape showing the Cartesian position vector, **R**, and the orientation vectors, **U**, **N** and **B** at the first (or reference) sensor pair and $\mathbf{U}_2$, $\mathbf{N}_2$ and $\mathbf{B}_2$ at the second sensor pair.

Shape Tape data are reported as projections onto a set of unit basis vectors – i.e. the **U**-vector is projected onto $\mathbf{u}_x$, $\mathbf{u}_y$ and $\mathbf{u}_z$. Bend or twist is computed as the change in the projection angles to the basis vectors between sensor pairs.

EXPERIMENTAL PROTOCOL

A custom-made model S1680 Shape Tape was used for the study. The Tape is 96-cm in length with a 12-cm sensor spacing. The output voltages from the fibre optic loops are multiplexed and digitized and the serialized data is read by dedicated Tape 2000 software. This data is processed to give the cartesian

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[1] Measurand Inc., Fredericton, NB Canada.

position and orientation vectors. The ability of the S1680 Shape Tape to detect joint angle was validated against an OptoTrak motion analysis system.

Static and dynamic testing of Shape Tape was done using an artificial leg, which is comprised of two segments. The lower segment is fixed to a wooden base and connected to the upper, or mobile, segment via a 6-DOF joint. The mobile segment can be moved, with respect to the fixed segment, independently about 3 axes: bend about the *y*-axis, representing flexion – extension; bend about the *x*-axis representing medial – lateral bend; and twist about the *z*-axis representing inversion – eversion. The Shape Tape was attached to the front surface of the artificial leg with the reference point (sensor pair 1) fixed to the bottom of the fixed segment, sensor pair 2 was fixed just below the joint and sensor pair 8 was fixed just above the joint. Three OptoTrak LED's were attached in orthogonal configuration to each of the mobile and fixed segments of the artificial leg. The experimental set-up is shown in Figure 2.

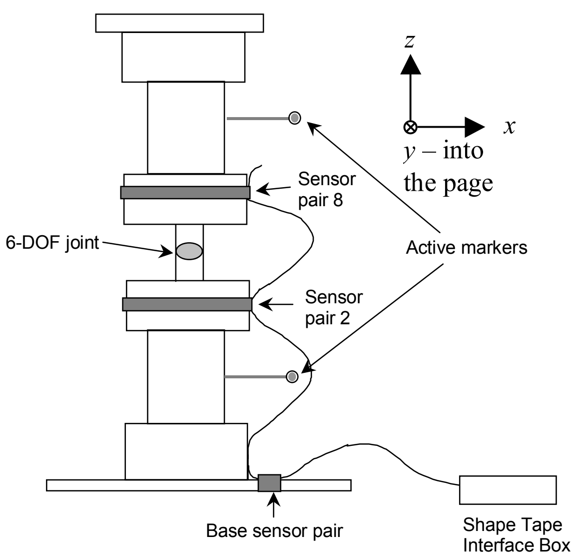


Figure 2: The experimental set-up showing the artificial leg, attachment of the Shape Tape and position of two of the OptoTrak markers.

The mobile segment was moved to a series of nominal static angles and locked in position. The angles were measured using a static goniometer. Flexion-extension (F/E), lateral-medial bend (M/L) and eversion-inversion (E/I) were tested independently. Table I gives the nominal static angles tested for each movement. Position data were acquired simultaneously from the Shape Tape and the OptoTrak. One hundred frames of Shape Tape data (approximately 23-s) and one hundred points (1-s) of OptoTrak data were collected for each angle.

Table I

Motion	**Nominal Static Angles**
F (+) / E(–)	50°, 40°, 20°, 0°, –10°
L(+) / M(–)	20°, 10°, 0°, –10°, –20°
E(+) / I(–)	30°, 15°, 0°, –15°

Dynamic motion in the F/E plane was studied. An angle of 45° was marked on the hinge which allowed movement about the y-axis. The hinge was unlocked and the mobile segment was moved manually from the straight position (0° flexion) to an angular displacement of approximately 45°. This was done for several cycles. The cycle period was approximately 2-s. Motion data were recorded simultaneously from the Shape Tape and OptoTrak for 15-s. OptoTrak data were sampled at 100 Hz; Shape Tape data were sampled at approximately 4 Hz. The test was repeated three times.

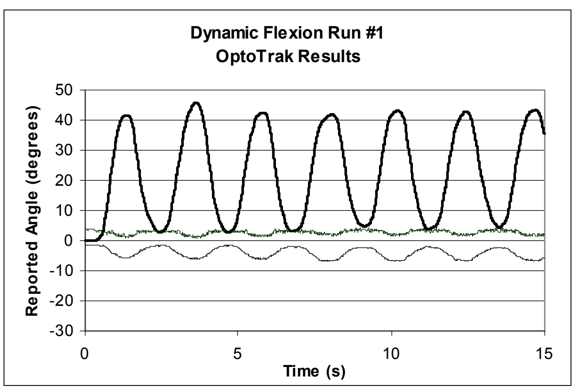
RESULTS

The static angles reported by the OptoTrak and Shape Tape are given in Table II. At the start of each series of measurements – F/E, L/M and E/I displacement respectively – data were collected for the straight condition, 0°. The reported values for the straight condition were subtracted from subsequent measurements.

Results for a single dynamic trial are shown in Figure 3 for Shape Tape and OptoTrak. A comparison of the reported rotation angle is shown in Figure 4.

Table II

Trial #	Motion	Nominal Angle (deg)	OptoTrak		Shape Tape	
			Mean angle (deg)	Std. Dev.	Mean angle (deg)	Std. Dev.
1	F/E	0	0.57	0.01	–2.26	0.09
2	F/E	40	37.77	0.00	45.33	1.61
3	F/E	20	17.07	0.00	23.95	0.08
4	F/E	50	45.19	0.01	51.51	0.25
5	F/E	–10	–9.79	0.01	–14.83	0.12
6	L/M	0	1.13	0.00	2.77	0.04
7	L/M	–20	–19.58	0.02	–1.08	0.04
8	L/M	–10	–10.56	0.01	–0.48	0.03
9	L/M	10	6.95	0.02	0.02	0.04
10	L/M	20	16.15	0.02	0.32	0.05
11	E/I	0	0.09	0.03	3.14	0.02
12	E/I	30	25.42	0.02	12.97	0.02
13	E/I	15	14.46	0.03	5.91	0.03
14	E/I	–15	–16.87	0.03	–9.56	0.12
15	Zero	0	–2.57	0.03	–2.16	0.04



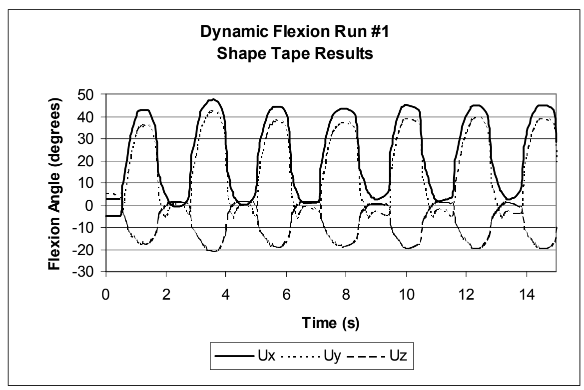


Figure 3: Measured dynamic flexion angles reported by OptoTrak and Shape Tape. Shape Tape angles were calculated using the individual component vectors, $\mathbf{u}_x$, $\mathbf{u}_y$ and $\mathbf{u}_z$**.** In the OptoTrak results the top trace is the F/E angle, the middle trace is the M/L angle and the bottom trace is the E/I angle.

DISCUSSION

In the static testing, Shape Tape performed reasonably well in determining F/E angles, or bend along the long axis. However, the angles calculated from the Shape Tape data are consistently larger than the angles reported by OptoTrak. This is likely due, primarily, to off-axis angles contributing to the calculated F/E angle. This issue is discussed later. Torsional twist, or E/I angles are under-reported by the Shape Tape. The under-reported E/I angles may be due to the inherent stiffness of the Shape Tape. The metal substrate of the tape can be twisted, however, because of its stiffness, it will try to resume its straight orientation. The Shape Tape may have lifted slightly under its attachment points giving less twist than was applied. Pure L/M bend, or bend along the short axis of the tape was simply not detected by Shape Tape. Given that Shape Tape is designed to

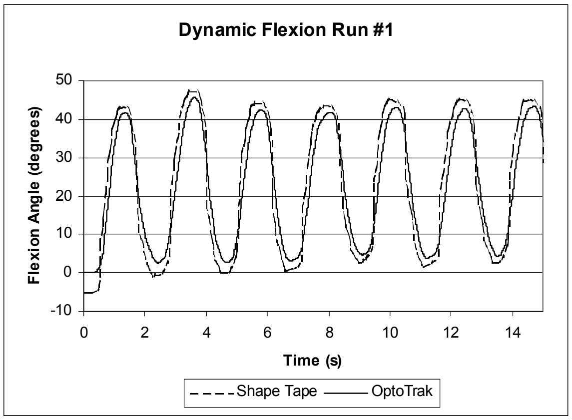


Figure 4: Comparison of rotation angle reported by OptoTrak and the $\mathbf{u}_x$ component vector angle reported by Shape Tape.

bend and twist along its length, M/L bend can be reliably detected only when there is also a bend and/or twist in the tape.

In the dynamic testing, the response of the Shape Tape is sufficient to track the change in the E/F rotation angle with time. However, again, the Shape Tape over-reports the angle as shown, for run #1, in Figure 4. The average errors in the peak-to-peak angles reported by Shape Tape vs. OptoTrak were: run #1: avg error = 5.143, SD = 2.443; run #2: avg error = 6.92, SD = 1.246; run #3: avg error = 6.803, SD = 0.561.

The Shape Tape performance can be explained in part by how the orientation data were processed. The angles between sensor pair 2 and pair 8 were calculated individually for the $\mathbf{u}_x$, $\mathbf{u}_y$ and $\mathbf{u}_z$ projections. Since $\mathbf{u}_x$ is oriented along the long axis of the tape, the angles calculated for the $\mathbf{u}_x$ projections were considered to represent F/E angle. However, the $\mathbf{u}_x$ vector component also tracks motion in the *xz*-plane. Thus, any off-axis L/M motion will also contribute to the angle of the $\mathbf{u}_x$ projection vector. From the OptoTrak results shown in Figure 3, there is a small, but noticeable L/M motion during the dynamic rotation. It is likely that the overestimation of the rotation angle is due to this off-axis motion.

CONCLUSIONS

In order to use Shape Tape to measure joint angles in a portable monitoring system, there are two requirements: accurate reporting and accurate positioning. Shape Tape was found to operate acceptably well in detecting bend along its long axis. It is likely that the dynamic results can be made more accurate by removing the M/L contribution to the calculated angle. The data re-processing is currently being done. More investigation is required to determine whether there are attachment configurations for which more accurate reporting of E/I and L/M angles can be achieved.

In attaching Shape Tape to a human limb to track one or more joint angles, it is important that the sensor pairs be aligned with anatomical landmarks and securely fastened. There must be sufficient slack in the tape to allow for movement of the limb without shifting the relvant sensor pairs with respect to the anatomy. The Shape Tape must also be comfortable and not interfere with, or alter, the activity patterns of the subject An investigation of these attachment issues is currently underway.

ACKNOWLEDGEMENTS

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