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Brief report

A transducer to measure isometric elbow moments

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Abstract

Objective. The purpose of this study was to design and implement a transducer to measure accurately the isometric elbow moments produced by individuals with tetraplegia.

Design. The device needed to be insensitive to off-axis moments and proximal joint motions and be capable of being used over a wide range of elbow and shoulder positions in an outpatient clinic setting.

Background. Measurement of the smaller isometric moments produced by individuals with tetraplegia is especially sensitive to the errors that can be introduced by inaccurate lever arm determination, off-axis loads, and proximal joint motions. Devices traditionally utilized for quantifying isometric strength are difficult to implement for the spinal cord injured population.

Methods. The elbow moment transducer consists of two four-bar parallelogram linkages joined by a lockable pivot. Strain gauges mounted on one beam of the parallelogram produce an output proportional to the elbow moment.

Results. Calibration of the device indicates that it accurately quantifies isometric elbow moments over a range that is appropriate for evaluating elbow extension strength in individuals with tetraplegia.

Conclusions. A device was developed and implemented that accurately quantifies isometric elbow moments over a range that is appropriate for evaluating elbow extension strength in individuals with tetraplegia.

Relevance

The ability to quantitatively evaluate elbow strength in persons with tetraplegia is useful for understanding and improving the clinical outcomes of rehabilitative interventions that involve the elbow. Published by Elsevier Science Ltd.

Keywords: Transducer; Elbow moment; Functional electrical stimulation; Tetraplegia; Tendon transfer

1. Introduction

The objective of this study was to develop and implement a transducer, manageable in a clinical setting, for quantifying isometric moments produced at the elbow joint by individuals with tetraplegia. Standard methods for quantifying isometric joint moments are subject to a number of error sources. For example, multi-axis force transducers, Cybex™, Biodex™, and other devices [1] measure force produced at a distance from the joint, which requires precise alignment of the sensor relative to the axis of rotation and knowledge of the lever arm to calculate the joint moment. Accurately identifying the joint center can be challenging and an error in lever arm estimation is directly transferred to the calculated moment. In addition, these devices cannot distinguish between the force that is transmitted to the sensor as a result of the joint moment being produced and forces produced in the same direction that are generated simultaneously by other means (e.g., proximal joint motions or weight shifts).

In particular, we aimed to develop an apparatus that could be mounted easily and quickly on arms of various sizes and that:

1. accurately measures isometric moments produced at the elbow joint (in extension and flexion) over a wide range of elbow and shoulder positions,
2. is not sensitive to proximal joint motions or off-axis moments that may occur simultaneously,
3. will quantify joint moments over a range of magnitudes that encompasses residual and restored elbow extension strength of tetraplegic individuals.

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2. Methods

The elbow moment transducer (EMT) consists of two four-bar parallelogram linkages joined by a lockable pivot (Fig. 1), and is based on an apparatus developed for measuring moments about the finger joints [2]. The dual parallelogram linkage restricts rotation but allows translation in the plane of elbow flexion–extension. Thus, an extension or flexion moment about the elbow produces a bending stress on the outer beams of the parallelograms, but the device cannot sense a force that is applied in the plane [2]. This design eliminates the need to measure a force and multiply by an estimated lever arm; and prevents forces produced by proximal joint motions or weight shifts from being misinterpreted as elbow moments.

The elements of the parallelogram are connected via stainless steel roller bearings and the outer beam is bolted to adjustable cuffs, which are used to mount the device on a subject's upper arm and forearm. The lockable pivot allows the elbow to be positioned between 0° (full extension) and 135° flexion. The EMT has a mass of 609 g. A plate between the beam and the cuffs allows the transducer to be connected to a support with a rigid base so that the subject does not have to support the weight of the device (Fig. 1).

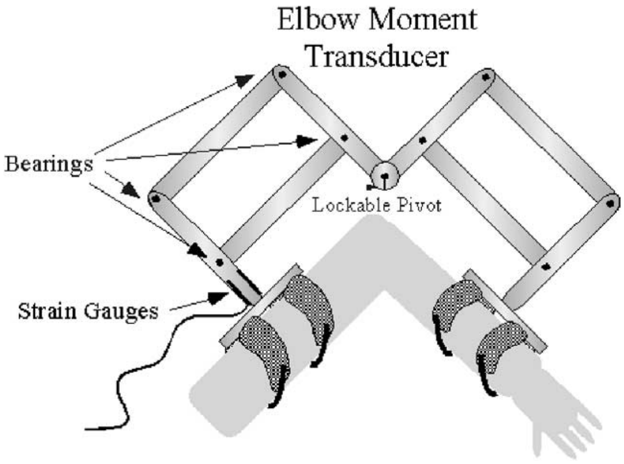

Fig. 1. Illustration of the elbow moment transducer. The transducer measures moments rather than forces because the dual parallelogram linkage prevents the transmission of forces in the plane of elbow flexion while the lockable pivot restricts elbow rotation. The transducer can be positioned in a broad range of elbow postures.

2.1. Transducer calibration

The EMT was calibrated by attaching it to a mock elbow that consisted of two hinged aluminum beams. The mock elbow was loaded with 10 known weights at a fixed distance from the center of rotation, producing an applied moment range 0.29–14.57 N·m. Calibration data were collected in a number of different conditions that were intended to simulate experimental conditions. Initially, the transducer was calibrated with the mock elbow joint positioned at 90° elbow flexion and 0° shoulder abduction (i.e., elbow flexion occurs in the sagittal plane). Flexion and extension moments ranging from 0 to 14.57 N·m were applied. Second, the output of the transducer was tested at three different elbow positions (30°, 60°, and 120°) with applied moments ranging from 0 to 14.57 N·m in extension and from 0 to 5.83 N·m in flexion. Third, calibration data were collected in the presence of off-axis loads. The transducer was positioned at 90° elbow flexion and simultaneously loaded with extension moments ranging from 0 to 14.57 N·m and pronation/supination moments ranging from −2.75 to 2.75 N·m; or extension moments ranging from 0 to 14.57 N·m and varus/valgus moments ranging from −2.91 to 2.91 N·m. Finally, the transducer was positioned to simulate different shoulder positions: 90° shoulder abduction (i.e., elbow flexion occurs in the transverse plane) and 45° shoulder abduction. In these positions, the transducer was loaded with extension moments ranging from 0 to 2.91 N·m. A linear regression model, analysis of covariance, was used to define the relationship between the voltage output of the transducer and the applied moment.

3. Results

The regression analysis indicates that separate calibrations for flexion and extension are required (Table 1). The output of the transducer was linear between −15 and 15 N·m (Fig. 2). The maximum error of the device was 0.36 N·m over the extension range, and 0.15 N·m

Table 1
Calibration summary for the elbow moment transducer

	Calibration equation		Accuracy	
		r^2	(moment >1) N·m)[a]	(moment ⩽ 1 N·m)[b]
Extension	$M = 5.3660(V) + 0.0339$	0.9997	⩽ 1.03% of moment	0.01 N·m
Flexion	$M = 5.0077(V) + 0.0109$	0.9996	⩽ 1.24% of moment	0.02 N·m

[a] Half of the width of the 95% prediction interval, expressed as a percentage of the predicted moment.

[b] Standard error of the predicted moment.

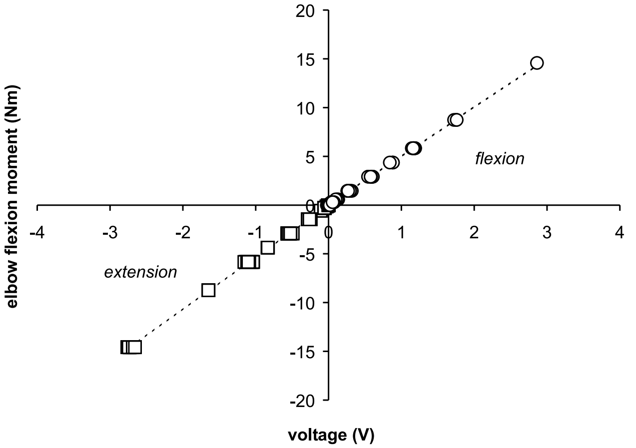

Fig. 2. Calibration data and regression lines (dashed lines). Flexion is positive; extension is negative. Symbols include all calibration data, including data collected at different joint angles, in the presence of off-axis loads, and with the device in different orientations relative to gravity.

over the flexion range. The position of the elbow joint, the presence of off-axis loads, and the position of the shoulder joint did not influence the output of the transducer in a clinically meaningful way. For example, when separate calibration equations were made for the trials involving different elbow positions, off-axis loads, and shoulder positions, then the maximum difference between the moment predicted by these equations and the moment predicted using the extension equation was 0.34 N · m (6% of the applied extension moment).

4. Discussion

A transducer has been developed and implemented that accurately measures isometric elbow extension and flexion moments, does not require identification of the axis of rotation, and is not sensitive to off-axis moments. The EMT can be used to quantify isometric moments produced over a broad range of elbow positions and limb orientations.

The transducer was designed to accurately quantify the small elbow extension moments produced by persons with tetraplegia. If desired, the EMT could be modified to accommodate a higher moment range by decreasing the gain of the signal conditioner, by utilizing thicker beams in the linkages, and by providing a crossbar between the linkages to reinforce the lockable pivot.

The elbow moment transducer has proven to be a useful and tractable measurement tool in our clinical research laboratory. We have found that the transducer is mounted easily on either the left or right arm and requires minimal adjustments to accommodate for differences in arm sizes across subjects. We have utilized the transducer to measure isometric moments produced at the elbow joint by numerous individuals with tetraplegia during voluntary effort and during electrical stimulation of the triceps [3].

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References

[1] Boissy P, Bourbonnais D, Gravel D, Arsenault AB, Leblanc M. A static dynamometer measuring simultaneous torques exerted at the upper limb. IEEE Trans Rehabil Eng 1998;6(3):309–15.

[2] Kilgore KL, Lauer RT, Peckham PH. A transducer for the measurement of finger joint moments. IEEE Trans Rehabil Eng 1998;6(4):424–9.

[3] Crago PE, Memberg WD, Usey MK, Keith MW, Kirsch RF, Chapman GJ, et al. An elbow extension neuroprosthesis for individuals with tetraplegia. IEEE Trans Rehabil Eng 1998;6(1): 1–6.