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Brief report

Three-dimensionality of contact forces during clinical manual examination and treatment: A new measuring system

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Abstract

Objective. Three-dimensionality (3D) of manual contact forces at the patient–practitioner interface.

Design. Description of a new hand/palm-held computerized 3D force measuring system.

Background. Up until now instrumented direct manual contact force measurement has been one-dimensional (1D).

Methods. The system is built for interface (direct) measurement of 3D manual contact force with real-time data presentation. Static calibration was performed of the 3D force sensor with variable preloads to study their effect as well of the prototype system adapted for clinical manual examination and treatment.

Results. Calibration validity and reliability of the 3D force sensor under all but the 5 kN preload and of the new system showed systematic respective random errors in the order or smaller than one newton.

Conclusions. The new system enables, for the first time, recording and presenting of 3D manual contact forces at the patient–practitioner interface. 3D direct manual contact force measures have the potential to give a more complete and differentiated characterization of patient and practitioner forces than 1D forces. Clinical validity of the prototype system will have to be investigated, and for studying specific clinical manual handling techniques, obvious limitations require further development.

Relevance

Manual techniques play a prominent role in chiropractic, manual-therapy and -medicine, massage therapy and osteopathy. The more complete 3D manual contact force description also can help practitioners and students to improve both manual force perception and delivery skills by providing higher standardization and real-time objective feedback about performance.

Keywords: Three-dimensional contact force measurement; Manual examination and treatment forces

1. Introduction

Different professionals use manual contact forces and contact force measurement during clinical (patient-related) examination and treatment in many settings. Disciplines like chiropractic, manual medicine, manual therapy, massage therapy and osteopathy have, in this respect, a special position because of the importance of contact forces here for examination as well as treatment.

Contact forces are referred to as active in case of voluntary muscle activity by patients. In the absence of muscle activity by patients, whether voluntary or involuntary, contact forces are referred to as passive. Instrumented manual contact force measuring can be direct one-dimensional (1D) or indirect three-dimensional (3D). Direct measurement is defined as taking place at the interface of force delivery and force sensing. Indirect measurement takes place away from this interface, mostly there where patient or practitioner is supported, respectively, either by ground or examination-treatment table.

A hand/palm-held measurement system for 3D contact force enables direct measurement of 3D manual contact forces and thereby fills the gap between 1D direct and 3D indirect contact force measurement. One could deduce that, by definition, human actions are taking place in 3D space, as such 3D measures correspond with the real-life situation more than one- or two-dimensional measures. Authors however, also have

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stressed the importance of shear forces during manual examination and treatment [1–5]. From a biomechanical point of view one could argue that, if one's interest is in applying force to the human body, a steady point of force application can be realized by a certain combination of greater perpendicular and smaller shear forces as to reach a certain contact friction. This would result into a set of force application angles, which provide sufficient grip. Most active tests seem to rely heavily on perpendicular forces, as do some passive manual techniques [4]. Other manual techniques use a combination of similar shear and perpendicular forces to realize a certain direction of force with sufficient grip [6,7]. Techniques involving hand displacement over the body surface will involve shear forces greater than the perpendicular force. This means that for a complete description of manual techniques shear forces are essential.

The purpose of this study is to describe a hand/palm-held computerized force measurement system for direct measuring of 3D manual contact force, including static calibration characteristics.

2. Methods

The 3D force measuring chain consists of the following four components: (1) a 3D piezo-electric force sensor (Kistler varioCOMP multicomponent force sensor 9601A31, Kistler Instrumente AG Winterthur, Switzerland). Related to this force sensor, a local rectangular (orthogonal) coordinate system is defined. Fig. 1 shows the coordinate system projected on the built-in force sensor. F_z represents the perpendicular force, while F_x and F_y represent the shear forces; (2) a charge amplifier (Kistler multichannel charge amplifier 5034A3, Kistler Instrumente AG); (3) an analog–digital converter (ADC) (Advantech ADC-card PCL-1800, Advantech Co. Ltd. Taiwan); and (4) a PC with data acquisition and real-time data presentation software (Labview 5.1, National Instruments, Austin TX, USA). The software samples the voltage signal with a frequency of 50 Hz. This was the optimum frequency in order to have real-time 3D force–time and 3D force vector recordings on the computer screen. However, the ADC-card allows for much higher sample frequencies.

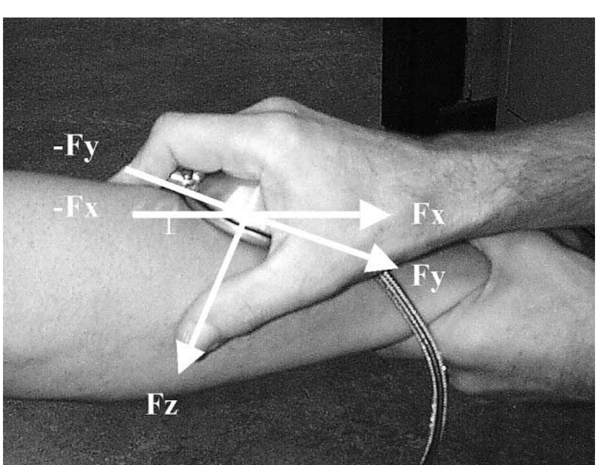


Fig. 1. Hand/palm held built-in 3D force sensor with local coordinate system. F_z represents the perpendicular force; F_x and F_y represent the shear forces.

The 3D force sensor must be mounted under preload in between two rigid non-contacting surfaces as to measure shear forces. For direct 3D force measurement, the manufacturer specifies a preload of 25 kN [8]. To study the effect of preload on calibration characteristics, the force sensor was mounted in between two aluminum circular plates and preloaded with a centered bolt at 5, 10, 15 and 20 kN. For shear force calibration two aluminum lever arms were used. Dead masses were used in a range of 0–25 kg. Measuring data were recorded in electrical voltage and converted by the data processing software to newton. Analysis was performed in a spreadsheet.

Inaccuracy was determined as: (1) Unreliability, by the standard deviation of random error, and (2) Invalidity, by four systematic errors. At (1) The standard deviation of random error is estimated in two ways. First by the standard deviation of repeated measurements, standard error of measurement (SEM) and second, by the deviation of the residuals of the calibration regression line, standard error of the estimate (SEE). For both quantities 95% confidence intervals (CIs) were calculated [9–11]. At (2) Systematic error is calculated in four parts. The first two parts are related to the slope (static sensitivity) and the Y-intercept (offset) of the least square calibration regression line. By taking the inverse of the slope and the negative of the Y-intercept, these two parts of systematic error can be adjusted for [9–11], so that errors stay $\leqslant 1$ N. The adjusted sensitivity and offset values were used for further measurements. The third and fourth part of systematic error was calculated as hysteresis and drift. Drift was measured during a 300 s time-trial without and with a load (15 or 25 kg) on the force sensor and expressed through a least square regression line. Besides, drift was calculated during the 60th and 300th second. From the drift data, also the smallest measurable output and smallest measurable output change could be determined.

For in vivo testing, the 3D force sensor is mounted, housed and preloaded with a bottom plate (26 cm^2), a segment of a sphere (maximal height : 27 mm) and a centered preloading bolt with a ring (Fig. 1). A series of static calibration measurements was executed with the 3D force measuring system in z-direction.

3. Results

With 1 N arbitrarily set as accuracy standard, an unacceptable drift >1 N was measured for F_z with 5 kN preload under all time and load conditons, and for F_x, F_y and F_z with all preloads under load during the 300 s time trial. Drift is a phenomenon, which may be caused by the capacitance of the preloaded sensor, by the capacitance of the cables or by the capacitance of the charge amplifier. Cabling and charge amplifier was guaranteed for by the manufacturer such that a certain drift at 25 °C of $\leqslant \pm 0.003$ pC/s takes place [8]. To adjust for drift the force sensor is left after preloading for two days. Besides, the system was reset after each measurement. Because of the high drift values of F_z at 5 kN preload, it was decided not to accept this preload. A preload of 10 kN is the lowest where static calibration characteristics are within the same order of magnitude as those measured at preloads of 15 and 20 kN. A low preload offers advantages from a mechanical engineering point of view in designing and building the force sensor housing with variable contact areas. For these reasons, it was decided to use a 10 kN preload for the 3D force measuring system.

The results for the static calibration of the 3D force sensor and the 3D force measuring system with 10 kN preload are displayed in Table 1. Exemplary data in the form of force–time diagrams of a chiropractic adjustments and a manual therapeutic manipulation are displayed in Fig. 2.

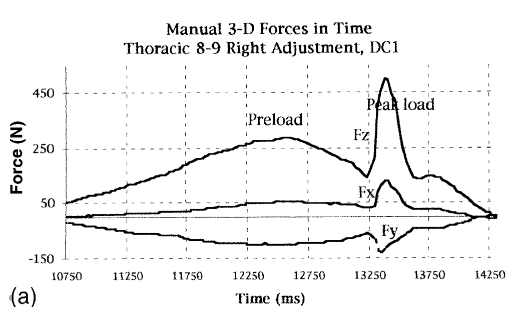
4. Discussion

It should be realised that accuracy is based on static sensitivity and offset measures which deviate $\leqslant 1$ N. This probably explains the rather small deviations for reliability and validity measures. Drift measures tend to be better for the built-in force sensor in z-direction, especially in the condition of no load. The sensor housing may provide a better stabilization of the sensor and its cable. For practical reasons, force ranges were set at 0–150 N for F_x and F_y, and at 0–250 N for F_z. Ranges that are small considering force magnitude data of chiropractic manipulations [3,7]. The smallest measurable output and output changes, 0.26–0.48 N for the three force components are related to the set force and voltage ranges and the 12-bit resolution of the ADC-card (0.2441 N/bit).

Table 1
Static calibration characteristics of the 3D force sensor in x-, y- and z-direction (F_x, F_y, F_z) and of the 3D force measuring system in z-direction. 10 kN preload

	3D force sensor			3D force measuring system
	F_x	F_y	F_z	F_z
Static sensitivity	0.9975	0.9952	0.9972	1.0024
Offset (N)	−0.0681	−0.2198	0.4524	−0.3737
Hysteresis (N)	$\leqslant$ 0.1969	$\leqslant$ 0.1398	$\leqslant$ 0.3362	
Drift				
0 kg ($f(s)$)	$-0.0006s + 0.0875$	$-0.0005s + 0.3506$	$0.0065s + 0.2395$	$0.0000s - 0.348$
after 60 s (N)	0.1472	−0.2144	0.4036	0.0000
after 300 s (N)	−0.0088	−0.2144	2.4222	0.0000
15–15–25 kg ($f(s)$)	$-0.0025s + 145.36$	$-0.0025s + 146.62$	$-0.0025s + 248.14$	$-0.0014s + 245.46$
after 60 s (N)	−1.0393	−1.1160	−0.4616	−0.0672
after 300 s (N)	−2.0255	−1.3840	−0.8654	−1.0442
SEM (N)	$\leqslant$ 0.1754	$\leqslant$ 0.3775	$\leqslant$ 0.6417	
95% CI	0.3611	1.5284	2.5371	
SEE (N)	0.4375	0.4808	0.6975	0.4478
95% CI	0.9157	1.0386	1.4432	1.4250
Range (N)	0–150	0–150	0–250	0–250
Smallest output and change (N)	0.260	0.268	0.289	0.348–0.477

$f(s)$: Function of time; SEM: standard error of measurement; SEE: standard error of the estimate; CI: confidence interval.



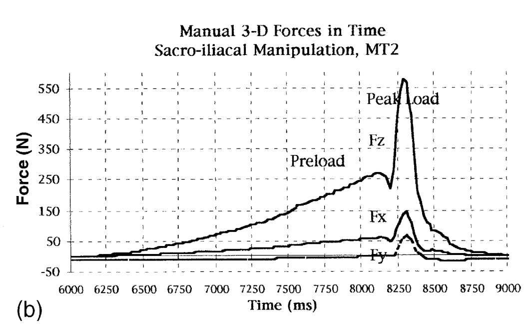


Fig. 2. (a, b) Typical 3D force–time profiles of a chiropractic vertebral adjustments (left) and a manual therapeutic pelvic manipulation (right).

Although 3D manual contact forces during clinical examination and treatment techniques can be measured with the system, one might question its clinical validity. Regarding the concurrent validity of the system with existing 1D instrumented manual muscle testing sytems for measuring active forces and 1D instrumented pressure threshold-tolerance measuring systems that measure passive patient forces, it is to be expected that the new system will be able to lead to comparable or even higher standards. Adjustments of the contact surface can be taken to accomplish such comparisons. In contrast, concurrent clinical validity of the system with existing instrumented direct and indirect systems for measuring, passive, manual contact forces may be more problematic. A rigid object of a defined size including contact surface (26 cm^2) disturbs the practitioner–patient contact. Because of the above, one may argue that practitioner's haptic feedback during force delivery and perception of force vector characteristics might differ and be inferior to the situation with an unhindered or less disturbed patient–practitioner contact as is the case with existing measuring systems. The only way to find out is actual concurrent validity research of measurement systems. One may also argue that the contact area of the system is too large for its application to small joints or over complex vertebral regions via spinous or transverse processes. All this means, that in its present form the prototype system has its limitations in measuring actual clinical handling techniques and that further development is required. In order to reach a more specific localization, smaller contact surfaces have to be used. The importance of contact area measurements was noticed by Kirstukas and Backman [3] and recently analysed by Herzog et al. [12]. In this respect, the lower preload provides more freedom to the mechanical engineering design of the housing. Notice that the ADC-card allows for kiloHertz sample frequencies, permitting more accurate force magnitude readings and cavitation recording. This latter can contribute to establish an aspect of clinical validity of certain manipulative treatments.

The system can also be useful to practitioners and students, to describe and develop their manual force perception and force delivering skills by providing standardization and real-time objective feedback regarding actions performed.

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References

[1] Gál JM, Herzog W, Kawchuk GN, Conway PJ, Zhang Y. Forces and relative vertebral movements during spinal manipulative therapy to unembalmed postrigor human cadavers; pecularities associated with joint cavitation. J Manipul Physiol Ther 1995; 18:4–9.
[2] Harms MC, Cusick G, Bader DL. Measurement of spinal mobilisation forces. Physiotherapy 1995;81:599–604.
[3] Kirstukas SJ, Backman JA. Physician-applied contact pressure and table force response during unilateral thoracic manipulation. J Manipul Physiol Ther 1999;22:269–79.
[4] Matyas TA, Bach TM. The reliability of selected techniques in clinical arthrometrics. Aust J Physiother 1985;31:175–99.
[5] Swenson RS. Point of view. Spine 2001;26:2110–1.
[6] Triano JJ. Studies on the biomechanical effect of a spinal adjustment. J Manipul Physiol Ther 1992;15:71–5.
[7] Triano JJ, Schulz AB. Loads transmitted during lumbosacral spinal manipulative therapy. Spine 1997;22:1955–64.
[8] VarioCOMP multicomponent force sensor. Winterthur, Switzerland: Kistler Instrumente AG, 1997 Piezo-Instrumentation Kistler Nr. 6.9601, ed. 6.97.
[9] Doebelin EO. Measurement systems. fourth ed. New York: McGraw-Hill Inc.; 1990.
[10] Portney LG, Watkins MP. Foundations of clinical research. Norwalk, Connecticut: Appleton & Lange; 1993.
[11] van den Eijnde PFHM. Meettechniek en Meetsystemen, tweede druk. Rijswijk, Nederland: Nijgh & Van Ditmar Educatief; 1991.
[12] Herzog W, Kats M, Symonis B. The effective forces transmitted by high-speed, low amplitude thoracic manipulation. Spine 2001;26: 2105–11.