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Characterization of multi-finger twist motion toward robotic rehabilitation

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Abstract— **Stroke or other neurological disorders potentially lead to movement deficits that may be recovered through proper rehabilitation. Robotic therapy has been applied to larger limbs such as the arms but not as commonly for the hand. It has been shown that virtual robotic environment with feedback distortion has a positive therapeutic effect in single finger movement. To expand this one finger therapeutic environment to more functional movements, our particular interest is applying feedback distortion to the everyday motor task of twisting bottle caps and jar lids. In order to understand what parameters to distort, unimpaired subjects' stereotypical movements were characterized with an intention to identify the differences with impaired population groups. This paper describes the hardware and software details of the haptic rotational twist-cap device developed to characterize, diagnose, and rehabilitate coordinated multi-finger twist movements. Using this device, it is shown the tangential and radial forces applied by each finger have stereotypical profiles for the unimpaired population. In addition, individual results from stroke, multiple-sclerosis (MS), and elderly subject population are presented. This preliminary data show different types of deviation from the control data providing insight into parameters that should be distorted during robotic rehabilitation.**

I. INTRODUCTION

Seventy percent of all patients have limited fine hand use in the first week, 41% at 3 months and 45% at 18 months after stroke [1]. Although there is evidence to the fact that vigorous early intervention after stroke may exacerbate brain damage [2] there is general consensus to the fact that early intervention after the patient is medically stable is ideal (after about 5-7 days after stroke) to promote neuroplasticity [3] and should include repetitive hand and finger motions [4]. There is also ample evidence that shows that incorporating functional tasks in rehabilitation protocols translates into far better outcomes [5] in comparison to uni-planar experimental tasks or tasks practiced in parts. Upper extremity functional performance is highly dependent on recovery of the hand due to the vast repertoire of movements contributing to function are dependent on dexterity of the hand [6] and thus this should be the part of training during recovery. Hand recovery has been a challenge partly due to the fact that the hand is affected to a greater degree to begin with, due to the extensive representation of the hand in the cortical homunculus, but also due to the fact that it is often neglected during rehabilitation. Conventional rehabilitation approaches utilizing exercise, orthotic support as well as electrical stimulation have shown that good recovery can be achieved in the hand in spite of some of the challenges associated with rehabilitation of the hand [7], [8], [9]. Despite strong evidence supporting this notion, research in rehabilitation after stroke using robotics has focused on training large-amplitude proximal joint movements, thus neglecting fine motor control related to the hand. Another major challenge for related technological developments is to provide engaging patient-tailored task oriented arm-hand training in natural environments with patient-tailored feedback to support (re)learning of motor skills [10]. Haptic devices are capable of not only providing realistic functional environments, but also providing focused and tailored feedback specific to individual requirements.

Some unique contributions of robotic therapy versus conventional therapies are that robots can be used as valuable adjuncts to save time and energy for the therapist, making rehabilitation sessions more efficient, and that rehabilitation protocols can be very precisely tailored to individual patients with only as much assistance provided as needed. The same protocols can also be used for objective assessment of improvement in status due to the capability of advanced sensing technologies available with the use of such devices. One of the important components of hand function is being able to control grasp during static conditions (holding objects without letting them slip) and under dynamic conditions (opening jars, transporting objects). Functionally relevant tasks have been shown to be of greater benefit for recovery after stroke [5].

Recently our group introduced the concept of feedback distortion, i.e., to introduce an undisclosed discrepancy between the actual movements and the virtual visual feedback the subjects receive about their movement [11], [12]. Feedback distortion targets individuals with chronic stroke and traumatic brain injury (TBI). These individuals have the capacity to make functional improvements; however, they may self-impose limits on their performance due to entrenched habits or psychological barriers [11]. Previously, a single finger therapeutic paradigm has been implemented using visual distortion in the virtual robotic environment [13]. This study has shown the finger's range of motion to increase by more than 50%, a spasticity measure (Ashworth score) to be reduced, and functional scores (such as the AMAT score) to improve after 6 weeks of therapy for

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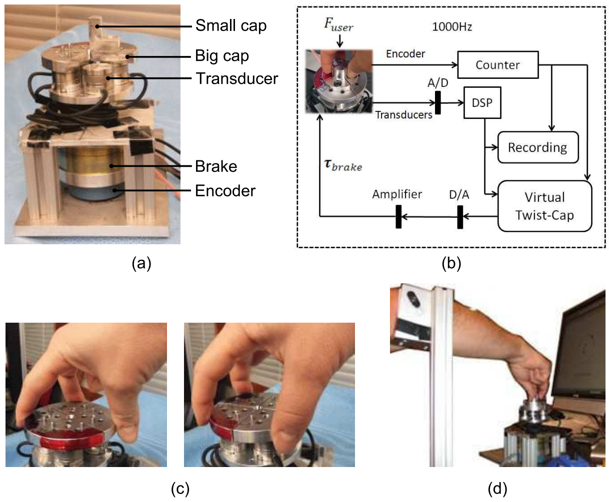

Fig. 1. Twist-cap device. (a) Picture of the twist-cap device intended to characterize, diagnose, and rehabilitate functional twisting movement. Here, one of the quadrant's small cap pieces is left on to demonstrate that these pieces can be added to make different size caps. (b) Diagram of the measurement setup. (c). Finger positions for THI (left) where the index finger and the thumb are opposed to each other, and THM (right) where the middle finger and the thumb are opposed to each other. (d) Picture of the experimental set-up showing the elbow placed on the elbow-rest, the twist-cap device and a screen providing visual feedback (virtual cap).

subjects 2-8 years post injury. We have also shown that these improvements can be retained [14]. While this study has shown promise for the use of virtual robotic environment and the distorted feedback, it has worked with only one finger movemetnt at a time. In order to translate these applications into more coordinated movements that will have functional significance in the outcome, we aim to apply the similar distorted feedback paradigm for a multi-finger task. Specifically we chose the cap-twisting motion because these movements are heavily used in our daily tasks and is a simple extension of a single finger movement. Even with a simple three-finger twist movement, the total number of parameters potential for distortion suddenly explodes. For example, we can distort the finger position, force, force balance/coordinate between fingers, radial/tangential force balance, etc. Therefore, in order to understand what to distort to improve the function, we must first understand what the stereotypical movements are like in healthy young subjects and compare the differences with different subject groups who have difficult time producing the twisting motion.

In this paper, we describe the hardware and software details of the haptic rotational twist-cap device developed to characterize, diagnose, and rehabilitate coordinated multi-finger twist movements and present normative data of a younger able-bodied subject group. We also have a small set of preliminary results from stroke, multiple-sclerosis (MS), and elderly subject population.

II. METHODS

A. *TWIST-CAP DEVICE*

The twist-cap device consists of four 6 DOF force/torque transducers (ATI Industrial Automation, Nano25) patterned radially about a central axis [15]. One side of the transducers is rigidly fixed to the rotor of a magnetic particle brake (Placid Industries, B15) as shown in Fig.1(a), which is driven by a linear amplifier (Trust Automation, TA105). The other side of each transducer is covered by circular quadrants, which together form the virtual twist-cap. Small gaps between each quadrant allow the transducer to detect an individual finger's motion exclusive of other digits force production. Smaller quadrants can be affixed on top of the transducers to provide different cap sizes. The rotation angle was measured by using an optical quadrature encoder (Agilent Technologies, HEDS-6540/T13) with a resolution of 0.18° (Fig.1.a).

Fig.1.b shows a diagram of the measurement set-up. The force/torque signals and the encoder output were digitized with a National Instruments data acquisition board (6071E) at a rate of 1000 Hz, and then stored to disk. Additionally real-time feedback on the cap position was presented on the screen (virtual cap). The device also has the capability to provide real-time feedback of the force/torques. Signal conditioning can be found in II-D.1. The software was implemented by using Matlab/Simulink (The MathWorks, Inc., Natick, MA, USA) and the Real Time Windows Target toolbox.

B. *EXPERIMENTAL PARADIGM*

To characterize twisting strategies, we recorded data from three fingers during different experimental conditions. These were:

- Two finger positions. Either the index finger (condition THI) or the middle finger (condition THM) was opposite to the thumb. The third finger was placed on the intermediate position (Fig.1(c)).
- Two cap sizes. The small cap had a radius $R = 12\,mm$ (condition SML) and the large cap size had $R = 44\,mm$ (condition LRG).
- Two twist directions. Clock-wise (condition CLW) or counter-clockwise (condition CCW).
- Two force levels based on the maximum force production level which was measured during the calibration phase. The level was either 40% (condition F40) or 60% (condition F60) of the maximum voluntary force level.

The experiment consisted of four sets of 20 trials each. Alternately experiments started either with the large (LRG) or small (SML) cap and with finger position THI or THM. For each trial subjects had the task of twisting the cap according to the finger position and direction (CLW vs. CCW) presented on the screen. The rotational movement was subdivided into two 90 degree twists, each requiring the subject to grasp the cap, perform a 90 degree twist and release the cap. After the first 90 degree twist the screen was blanked for 500 ms before the go signal for the second twist was shown. The direction of the twists was alternating from trial to trial (random at the beginning). The force levels F40 and F60 were randomly distributed over the trials. To avoid arm or body usage and to ensure that finger and wrist were used to perform the motor task, the right elbow was placed on an elbow-rest (Fig.1(d)). No feedback distortion was presented to subjects.

The maximum comfortable force production level F_{MAX} for each subject was measured individually for conditions SML and BIG. Subjects were told to produce a constant maximum twisting force that could be comfortably maintained for 3 s. F_{MAX} was defined as the average force of the 3-s period.

C. SUBJECTS

Thirteen right-handed volunteers participated in the twist-cap experiment:

- Ten young able-bodied individuals (24.9±6.6 yr, 8 male, 2 female) constituted the control group. All were without any medical or psychological disease and had normal or corrected to normal vision.
- One 64 yr old woman was a stroke age-matched group. She was a spectacle wearer and under medical treatment for arthritis. This subject did not feel comfortable twisting the large cap under finger condition THM.
- One 52 yr old man with multiple sclerosis (MS) affecting primarily his sensory feedback.
- One 88 yr old man who had a stroke in the year 2000. He was able to manipulate objects with his right hand, however, he had problems turning on a water tap or opening soda bottles. Furthermore, since his episode the patient was sensitive to pain, especially in his legs and index finger. To manage pain, we did not conduct (THI, BIG) and (THM, SML) conditions.

All subjects gave informed consent after the aim of the study and the experimental procedure had been explained to them. The study had been reviewed and approved by the University of Washington institutional review board.

D. DATA ANALYSIS

1) SIGNAL CONDITIONG : At the beginning of each experiment 10 s baseline data were collected. During this period subjects were not touching the twist-cap. By subtracting the average value of the baseline and by multiplication with the transducer calibration matrix, the recorded signals were converted into forces/torques. A 5^{th} order Butterworth low-pass filter with cut-off frequency at 8 Hz was was used to smooth the data.

2) RADIAL AND TANGENTIAL FORCES: We are interested in the radial (F_{rad}) and tangential (F_{tan}) forces applied to each quadrant of the cap from thumb, index and middle finger. To compute F_{rad} and F_{tan} we need to identify the position of the finger on the twist cap quadrant. Fig.2 illustrates this problem. Let $\vec{F}$ denote the force acting at point $\vec{P_3}$ of the quadrant (radius R). Operating under the assumption that inertial interactions are negligible, a static analysis can be used to solve for $\vec{P_3}$ given the transducer reactions, F_x, F_y, and torque M_z. First a normal is defined relative to the orientation of the transducer's force reaction,

$$\hat{F}_{\perp} = \vec{F} \times \hat{Z} \tag{1}$$

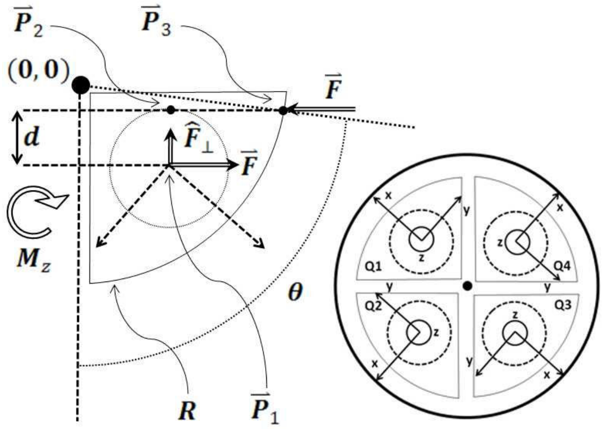

Fig. 2. Cartoon illustrating the computation of the finger position on the cap (angle Θ). The scheme on the right side shows the axes of the transducers (planview).

Where $\hat{Z}$ is a unit vector along z. Due to the statics of the situation we can solve for the perpendicular moment arm of the finger force about the transducer. The length of the lever arm d can be computed according to,

$$d = M_z / \|F\| \tag{2}$$

A point on the finger force's line of action can now be found by traveling the distance d along the vector $\hat{F}_{\perp}$ starting from the transducer's center, $\vec{P_1}$. This results in the point, $\vec{P_2}$,

$$\vec{P_2} = \vec{P_1} + d \cdot \hat{F}_N \tag{3}$$

The direction of finger force is already known, $\hat{F}$, therefore the final step to locate $\vec{P_3}$ is to determine the intersection of the force's line of action through $\vec{P_2}$ with the quadrants perimeter. The equation representing this condition is given by,

$$\left| \vec{P_2} + t \cdot \hat{F} \right| = R \tag{4}$$

This equation can be expanded to form a quadratic in the parameter t. Solving for t, and plugging back into equation (4) results in $\vec{P_3}$. From $\vec{P_3}$, angle Θ can easily be generated using the arctangent. Finally the finger force can be decomposed, correctly, into F_{rad} and F_{tan} using the following transformation,

$$F_{rad} = \left(\vec{F} \bullet \hat{P_3} \right) \cdot \hat{P_3} \tag{5}$$

$$F_{tan} = \vec{F} - F_{rad}. \tag{6}$$

3) NORMALIZATION: In order to compare data across subjects, the computed time series were normalized. Trials were subdivided into 2 periods of interest, the pre-twisting (T_{pre}) and the twisting period (T_{twist}). T_{pre} period was defined as the time when the finger touch was first detected (t_{touch}) and when the cap started to rotate for the first 5° ($t_{5°}$). The t_{touch} was defined as when F_{rad} exceeded two standard deviations from the mean F_{rad} after the go signal was presented to the subject. For each trial the T_{pre} period was normalized by time (t_{touch} at 0 and $t_{5°}$ at 1) and the

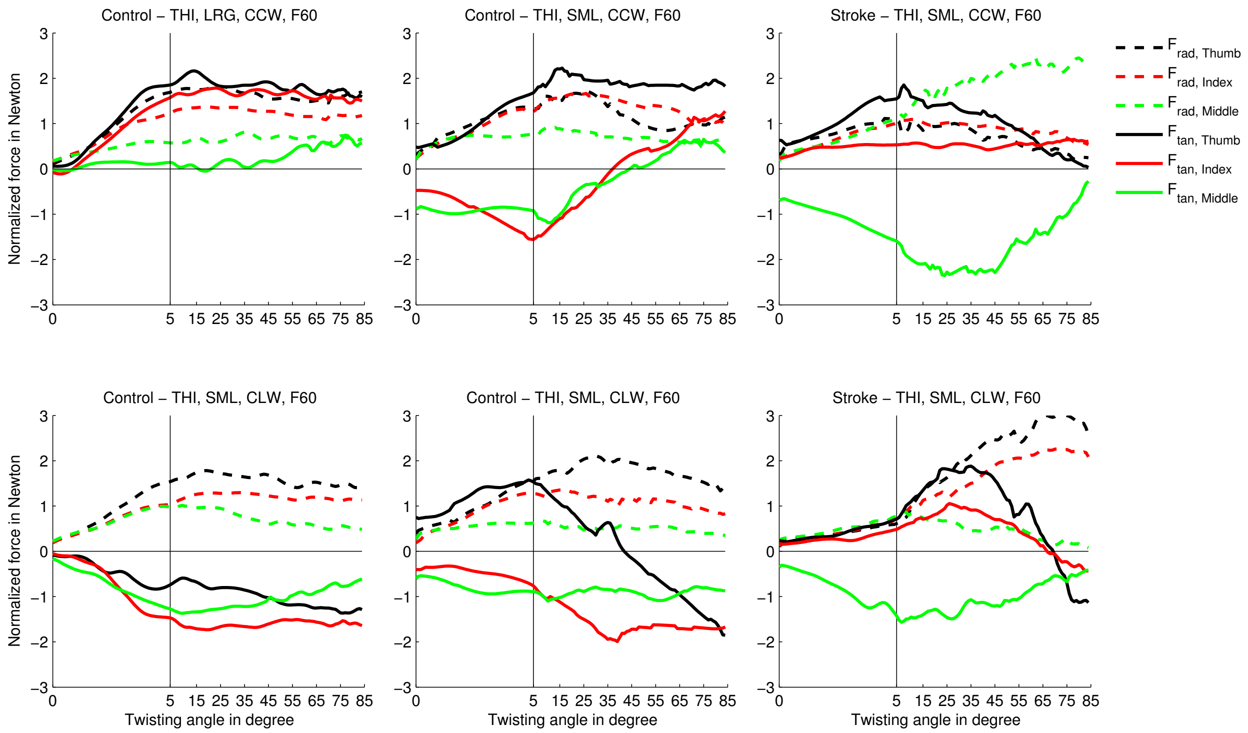

Fig. 3. Average F_{rad} and F_{tan} time course for thumb, index and middle finger for one typical control subject (column 1-2) and the stroke patient (column 3) for different conditions. F_{rad} toward the center of the cap are positive and thus all F_{rad} are positive. Positive F_{tan} contribute to CCW movement and negative F_{tan} contribute to CLW movement. The vertical line in each plot marks the border between T_{pre} and T_{twist}.

T_{twist} period by the twist cap angle between 5° and 85°. The average of the normalized trials was computed and rescaled by dividing the individual forces of each finger by the sum of forces applied by all three finger. F_{rad} and F_{tan} were rescaled individually.

4) IDENTIFICATION OF MOVEMENT PATTERNS: In order to find characteristic parameters across the control group, we computed correlations for different combinations of conditions. For each of the following three condition sets eight combinations, respectively, were analyzed: (finger position, cap size, twist direction), (finger position, cap size, force level) and (finger position, force level, twist direction). For each set the average value, the linear slope and the quadratic slope of the normalized F_{rad} and F_{tan} within T_{pre} and T_{twist} were investigated individually. For example for the combination (THI, SML, CLW) and parameter average F_{rad}, the average F_{rad} at force level F40 and F60 for thumb, index and middle finger were used to model the twist motion (6 parameters for each condition). To find characteristic movement patterns principle components analysis (PCA) was performed with the most correlated parameter for all combinations.

III. RESULTS

For T_{pre} and T_{twist} independently the average F_{rad} and F_{tan} were most correlated across all combination of conditions (average Pearson correlation coefficient 0.75). Our investigation therefore focused on this parameter.

Fig.3 shows example time courses of F_{rad} and F_{tan} for thumb, index and middle finger for conditions (THI, LRG, CLW, F60), (THI, LRG, CCW, F60), (THI, SML, CLW, F60) and (THI, SML, CCW, F60) for one typical control subject. Additionally results of the stroke patient are shown. F_{rad} toward the center of the cap is positive and thus all F_{rad} recorded during the trials are positive. Positive F_{tan} contribute to CCW movement and negative F_{tan} contribute to CLW movement. For the control subject the curves illustrate an increase of F_{rad} in T_{pre} followed by a steady or decrease in magnitude during T_{twist}. The stroke patient in contrast shows an increase of F_{rad} also during the latter. F_{tan} during the T_{twist} are characteristic for the direction of the twist motion for LRG. However, notice that one or more fingers produce a F_{tan} that is against the movement direction in some cases. The index/middle finger for CCW and thumb for CLW for SML are acting contrary to the twisting direction in the first third of the motion. This antagonist pattern is visible also for the stroke patient.

The average F_{rad} and F_{tan} for T_{pre} and T_{twist} are summarized in Fig.4 for all subjects. The plots show consistent force patterns for the control group for each finger. Paired t-tests confirm a significant increase from $F_{rad}(T_{pre})$ to $F_{rad}(T_{twist})$ for thumb (THI: 0.96±0.13 vs. 1.42±0.21, p=0.0001; THM: 0.94±0.14 vs. 1.34±0.26, p=0.0001), index finger (THI: 0.77±0.13 vs. 1.14±0.22, p=0.0001; THM:

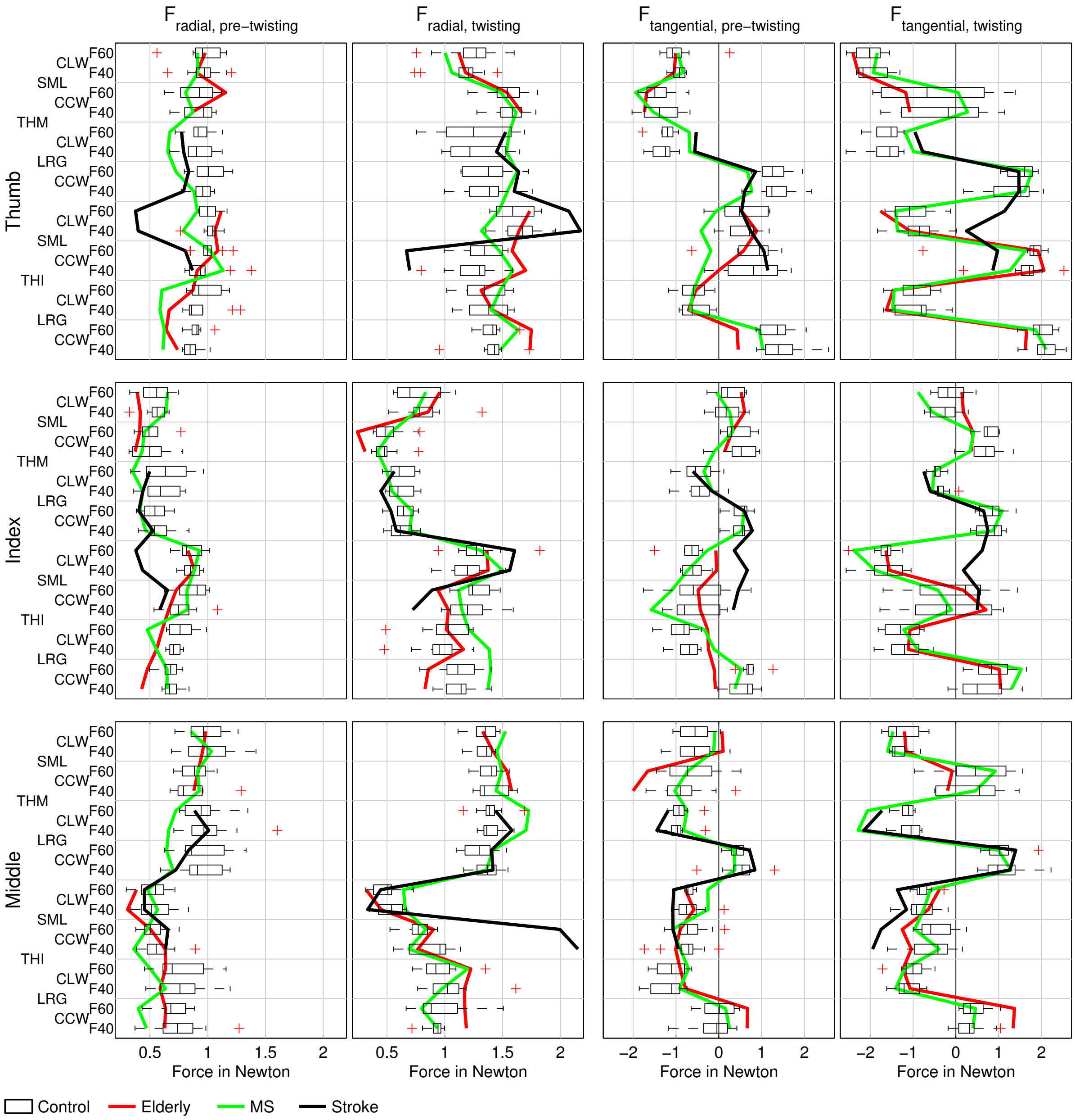

Fig. 4. F_{rad} and F_{tan} during T_{pre} and T_{twist}. The boxplots show the distribution of the control group. The boxes have lines at the 25^{th} percentile, median, and 75^{th} percentile. The lines extending from each end of the boxes (whiskers) show the extent of the rest of the data. Outliers, i.e., values beyond the end of the whiskers, are marked with the '+' symbol. Superimposed are the values for the elderly, MS and stroke.

0.56±0.15 vs. 0.64±0.17, p=0.0016) and middle finger (THI: 0.64±0.22 vs. 0.81±0.26, p=0.0001; THM: 0.94±0.20 vs. 1.364±0.12, p=0.0001). The correlation of $F_{tan}(T_{twist})$ of thumb, index and middle finger with the direction of twist motion was 0.93, 0.79 and 0.65, respectively, for THI; corresponding correlations for THM were 0.78, 0.87 and 0.88, respectively.

The average F_{tan} of the elderly subject (Fig.4) and of the individual with MS were within the distribution of the control group. For both individuals F_{rad} during T_{twist} were close to either the lower or the upper border of the distribution of the control group. The stroke patient showed a different pattern. F_{rad} and F_{tan} were beyond the bounds of the control group. While there was no correlation found between F_{rad} and F_{tan} for the control group (correlation coefficient < 0.2), the stroke subject showed a correlation (0.78) between F_{rad} and F_{tan} during T_{twist}.

Two principal components were required to represent minimum (average over conditions) 68%(74%) of F_{rad} and 74%(76%) of F_{tand} during T_{pre}. During T_{twist} two principal components represented 72%(79%) of F_{rad} and 72%(91%) of F_{tan}. Tab.I shows principal components for F_{tan} for conditions (THI, SML, CCW) and (THM, SML, CCW). In both cases two components account for about 80% of the

TABLE I

PRINCIPAL COMPONENTS FOR F_{tan}.

Condition	Finger	Components 1	Components 2
THI, SML, CCW, F40	Thumb	**0.919**	0.106
	Index	**0.888**	-0.330
	Middle	0.254	**0.885**
THI, SML, CCW, F60	Thumb	**0.929**	0.107
	Index	**0.877**	-0.281
	Middle	0.147	**0.799**
Cumulative %		55.9%	83.1%
THM, SML, CCW, F40	Thumb	0.473	**0.761**
	Index	**0.872**	-0.376
	Middle	**0.902**	-0.279
THM, SML, CCW, F40	Thumb	0.192	**0.952**
	Index	**0.924**	-0.160
	Middle	0.409	0.451
Cumulative %		47.6%	79.8 %

variance in the data. These results are consistent with the pattern in Fig.4.

IV. DISCUSSION

The control group results showed that subjects, in general, use a consistent strategy. There are a few characteristic parameters while making these movements. First, the finger that was opposing the thumb contributes more in radial force and twisting than the finger that is 90 degrees off from the thumb. Second, the thumb contributes the most in twisting when the index finger is opposed (THI), while the thumb contributes the least in twisting when the middle finger is opposed (THM).

Another interesting pattern is shown in Fig.3. The curve suggests that, depending on the twist direction and the relationship of the geometry of the cap and the hand posture, individual fingers produce forces which act against the twist direction. We believe that this opposite force contribution comes from the thumb kinematics that makes it difficult to produce assisting force for twisting in those configurations. The curves in Fig.3 and more clearly the distribution in Fig.4 show that the thumb produces highest radial forces for condition (THI, SML, CLW). The reason for this is that the force acts along the trajectory/axis of the thumb.

The F_{tan} of the elderly individual was within the range of the control group. Due to the arthritis the elderly subject could not stress the index finger. Consequently thumb and middle finger had to apply higher forces. For the MS patient the pattern suggest an increased radial forces for all fingers. This behavior may arise due to the loss of somatosensory feedback [16].

The chronic stroke patient showed a different pattern. The radial forces for the small cap were much higher compared to all other individuals. Furthermore, for this individual radial and tangential forces were correlated. One explanation for this behavior might be the pain the patient was experiencing. It may also be related to the disruption in the coordinated movement among fingers.

The preliminary results in this study suggest that radial and tangential forces can be used to characterize twist motion patterns. This is in accordance with the literature [17]. Furthermore, the force profile of the stroke patient suggests that these two parameter are suited for distortion feedback therapy.

Some of the described effects may be caused by the constraints imposed from the experimental paradigm. In real life people potentially use different strategies, e.g., the arm as lever to open a water bottle or the palm of the hand to open a jar. The set-up, however, allows the study of patterns of individual fingers and the interaction of multiple fingers.

The introduced twist-cap device is a small, compact robot able to provide haptic feedback without actuators. The brake is a passive mechanical element which makes the device safe and thus also suitable for home application. The system can be used to train the multi-finger and wrist coordination, strength, and pinching/twisting strategies.

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