Human Force Discrimination during Active Arm Motion for Force Feedback Design

Seyedshams Feyzabadi, Sirko Straube, Michele Folgheraiter, Elsa Andrea Kirchner, Su Kyoung Kim, and Jan Christian Albiez

Abstract—The goal of this study was to analyze the human ability of external force discrimination while actively moving the arm. With the approach presented here, we give an overview for the whole arm of the just-noticeable differences (JNDs) for controlled movements separately executed for the wrist, elbow, and shoulder joints. The work was originally motivated in the design phase of the actuation system of a wearable exoskeleton, which is used in a teleoperation scenario where force feedback should be provided to the subject. The amount of this force feedback has to be calibrated according to the human force discrimination abilities. In the experiments presented here, 10 subjects performed a series of movements facing an opposing force from a commercial haptic interface. Force changes had to be detected in a two-alternative forced choice task. For each of the three joints tested, perceptual thresholds were measured as absolute thresholds (no reference force) and three JNDs corresponding to three reference forces chosen. For this, we used the outcome of the QUEST procedure after 70 trials. Using these four measurements we computed the Weber fraction. Our results demonstrate that different Weber fractions can be measured with respect to the joint. These were 0.11, 0.13, and 0.08 for wrist, elbow, and shoulder, respectively. It is discussed that force perception may be affected by the number of muscles involved and the reproducibility of the movement itself. The minimum perceivable force, on average, was 0.04 N for all three joints.

Index Terms—Perception, psychophysics, biorobotics, human factors, wearable computers

1 Introduction

Haptic devices provide the user with force feedback, enabling proper interaction with real or virtual objects [1]. Nowadays, this interaction is becoming very detailed in applications where machines replace or extend limbs' capabilities as well as in cases where subjects have to immerge into sophisticated virtual scenarios. Exoskeletons are an example of haptic devices, where successful force discrimination of the human is essential for the close interaction with the machine. From the engineering point of view, it is possible to provide a wide range of force resolution to the human, but it is not immediately clear if the human is really able to perceive the intended changes. However, this question can be answered using psychophysical methods, which is what we do in the present study. The aim here is to measure the human force resolution to use the results for specification of requirements for an exoskeleton. More specifically, our goal is to measure the smallest force changes that a human can perceive with his arm. This analysis is important from three aspects: design, force feedback, and smooth movements.

Teleoperation with the exoskeleton happens in a dynamic environment, i.e., the force is applied to the human while s/he is actively moving. In contrast, most of previous works have concentrated on passive movements, where the body was considered to be fixed (such as [2], [3]).

Our approach bases on first defining a precise set of actively executed movements that are common in teleoperation scenarios and then measuring the force sensitivity during these executions. The feedback generated by the exoskeleton will use this measured force sensitivity to make sure that it is indeed perceived by the user. The intended exoskeleton will be used to teleoperate a robotics system and will cover both arms and the back of the user. For a reliable telemanipulation, the impression of a realistic percept is essential, i.e., an impression of being onsite strongly improves the human abilities to fulfill the task and to deal with unexpected situations. In this context, force feedback is used from the environment to facilitate the user's immersion into the scene during teleoperation [4]. The feedback received from the haptic interfaces (i.e., the exoskeleton) is usually sensed as external force by the user. As an example, a previous version of the exoskeleton is illustrated in Fig. 1. To get a more direct impression of the system depicted in Fig. 1 and an example of the teleoperation application, we refer the reader to the video, submitted as supplemental material, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/ToH.2013.4. It covers the right arm and is equipped with a total of nine DOFs, seven of which are actuated and two are purely passive. The

- *S. Feyzabadi, M. Folgheraiter, and J.C. Albiez are with the Robotics Innovation Center, German Research Center for Artificial Intelligence, Bremen, Germany.*
  E-mail: {shams.feyzabadi, michele.folgheraiter, jan.albiez}@dfki.de.
- *S. Straube is with the Robotics Lab, Faculty of Mathematics and Computer Science, University of Bremen, Bremen, Germany.*
  E-mail: sirko.straube@uni-bremen.de.
- *E.A. Kirchner and S.K. Kim are with the Robotics Innovation Center, German Research Center for Artificial Intelligence, Bremen, Germany, and Robotics Lab, Faculty of Mathematics and Computer Science, University of Bremen, Bremen, Germany. E-mail: {elsa.kirchner, su-kyoung.kim}@dfki.de.*

Manuscript received 23 Oct. 2012; revised 25 Jan. 2013; accepted 25 Jan. 2013; published online 12 Feb. 2013.
Recommended for acceptance by R. Klatzky.
For information on obtaining reprints of this article, please send e-mail to: toh@computer.org, and reference IEEECS Log Number TH-2012-10-0083.
Digital Object Identifier no. 10.1109/ToH.2013.4.

Fig. 1. A subject wearing the VI-Bot Exoskeleton. The three contact points to the arm, where force feedback is possible, are shown (1, wrist; 2, elbow; 3, shoulder). For more details on the system, see [5], [6].

kinematics is configured on the base of the human anatomy to maximize the usable workspace [5], [6] and to avoid restrictions to the user's movements. To deliver complex force patterns and to distribute the weight of the system over the body, three contact points were defined between the limb and the exoskeleton (see Fig. 1): shoulder, upper-arm, and forearm (wrist proximity). The system is actuated via a low-pressure hydraulic circuit operating at 25-30 bar. Each joint is equipped with position and torque sensors. In addition to that, at each contact point with the limb, the interaction forces can be measured via dedicated force/torque sensors.

For the design phase, choosing proper actuators for a wearable exoskeleton is a critical point. Precise actuators are usually complex and expensive. Having detailed knowledge about the human force perception helps the designers to select more suitable actuators. In addition, this knowledge will be used to compute the appropriate force feedback. Once the user manipulates the environment, s/he has to be aware of any obstacles, objects' displacement, and so on. The magnitude of force feedback must be calculated properly to establish a percept that the user can rely on. In this respect, too small differences will not be perceived, while too large feedback will confuse the user and may pull him out of the current task. This is of particular importance during tasks requiring fine-manipulations or taking place in fragile environments. In these cases, small magnitudes of force feedback are very important such as the beginning threshold of the force sensation while touching a fragile object. Finally, the force feedbacks, generated by the actuation system, should be performed with sufficient smoothness adjusted to human perception, for example, it should be avoided that force changes are smaller than perceivable for the human limb hindering successful interaction with the environment. In addition, as long as the actuation error of a system stays below the perceptual threshold, the user will not notice any error. Quite similar technology is nowadays used in animations [7]. Therefore, the complete design of the actuation system of the haptic interface can benefit from the information obtained in the present study.

The interaction between the haptic interface (here, the exoskeleton) and the target system is generally bidirectional, namely the position and applied force of the subject's limb is sensed by the interface and mapped to the target system (virtual or real), and concurrently the position/force measured in the target system (virtual or real) is displayed back to the user via the interface. In this manner, the interface enables an extension of the human sensory system allowing a better integration between the machine and the human. For this reason, the human sensory-motor system plays an important role in defining the performance of a haptic interface. The perceived stimulus does not only depend on the physical quantity, but is also conditioned by the instantaneous state of the somatosensory system [8]. It is, therefore, critical to know the relationship between the applied force and the force changes required to reach a noticeable difference for the subject. This relationship was measured for three contact points (wrist, elbow, and shoulder) of the human arm. We consider classical psychophysical methods used for this measurement as a crucial step in developing a robotic system designed to closely interact with a human.

The paper is structured as follows: Section 2 introduces some related works on force discrimination analysis. Section 3 describes the methods and experimental setup. Section 4 explains the results and analysis of them. Section 5 is assigned to discussions on the results. Section 6 concludes the paper, and raises some future research directions.

2 State of the Art

For a good quality of haptic feedback, i.e., to exert appropriate forces to elicit the intended sensation of the user, knowledge about human force sensitivity is mandatory. A classical framework for relating *physical* quantities to the *psychological* percept is provided by *psychophysics*, where the perception of a stimulus difference has been termed *difference threshold* or *just noticeable difference (JND)*. The minimum intensity value ϕ that a stimulus becomes perceivable is called *absolute threshold*.

In 1860, Fechner formulated a law, which he called *Weber's Law*, stating that the sensitivity to perceive a difference between two stimuli decreases with increasing size of the original intensity ϕ_0 [18]. The value of the JND, $\Delta\phi$, is the intensity difference corresponding to the perception of a stimulus with intensity ϕ_1 as different from ϕ_0. Fechner further states in this law that the ratio between $\Delta\phi$ and ϕ_0 stays constant, so that

$$\frac{\Delta\phi}{\phi_0} = c. \tag{1}$$

The constant c is called the *Weber Fraction*.

Nowadays, it is well known that this relationship is not true for every modality under every circumstance: Other sensory modalities can influence the JND measured in a single modality as was shown in, for example, [3], while the discrimination of force direction is influenced by visual congruency. Furthermore, it is a long standing fact that for very high or very low intensities, the ratio between $\Delta\phi$ and ϕ_0 changes. This has been shown, for example, for the sensitivity of rods in the human retina [19] or for acoustic intensity discrimination of high frequencies [20]. One way to compensate for this when measuring small stimulus

TABLE 1
Summary of Prior Works on Force Discrimination, m and f Represent Male and Female Subjects, Respectively

Related Paper	Test Point	No. Subjects	Weber Fraction	Application
[9]	Finger tip	20(18m, 2f)	5%	Push button design
[10]	Index finger	5m	10%	Rehabilitation
[3]	Index finger	20(15m, 5f)	-	Sensor/Actuator asymmetry
[11]	Index finger	23(11m, 12f)	19.7%-46%	Fine motor control
[12]	Two fingers	5m	7%	Grasping
[13]	Elbow	14(7m, 7f)	5.2%-8.8%	General experiment
[14]	Hand	6(2f, 4m)	-	Data compression
[15]	Hand	17(11m, 6f)	15%	Robot tele-operation
[16]	Both hands	12m	11.5%-16.5%	Car industry
[2]	Whole arm	3(1f, 2m)	1%-2%	General experiment
[17]	Foot	8(4m, 4f)	30%-50%	Car industry

intensities ϕ_0 close to 0 is to take into account the noise of the sensory system a [8]. This changes (1) to

$$\frac{\Delta\phi}{\phi_0 + a} = c. \tag{2}$$

This modification allows us to incorporate the absolute threshold at $F_{ref} = 0$ into the calculation of the Weber Fraction by avoiding division by zero, and has been used recently for computation of the Weber Fraction, for example, in [21].

The application of Weber's Law is still valid within limits and widely used in the literature showing that, for example, discrimination of tactile stimuli [22], auditory discrimination in an intermediate range [23], and judgment of numerical inequality [24] can be described with this relationship. The theory has been applied for human force discrimination as well [8]. However, the picture is not complete because most research has so far focused on specific fine manipulations with the hand or single fingers, the human arm or foot movements. In addition, the methods are varying in the way these measures were obtained: some experiments did not allow a movement, and fixed the respective body part (e.g., [2], [3]), while others did not specify a certain movement (e.g., [14]). Therefore, a direct comparison of the results is often difficult.

In the following, the existing works on human force discrimination of the arm are described, from single finger movements to movements of the whole arm. The important results for the current study are also listed in Table 1. The approaches in all of these studies are based on Weber's law.

For the index finger, JNDs not less than 5 percent have been reported in a task, where a user-friendly button was developed and finger tipping was investigated to simulate a push button with an opposing constant force [9]. Such studies have also been carried out in the context of rehabilitation applications using virtual environments [10], where the authors looked for thresholds of force sensitivity of the index finger so that they may ultimately construct therapeutic force feedback distortions that stay below these thresholds. In their study, Allin et al. reported JNDs around 10 percent. In [11], force perception of the index finger while rotating around the metacarpophalangeal (MCP) joint was investigated. They considered the effect of age. A stroke patient was also taken into account. The result of their research showed force JNDs between 19.7 and 46 percent.

For grasping with two fingers, JNDs around 7 percent have been observed [12] along with small influences of other task parameters such as speed and span distance. Here, a task was used where two plates should be grasped with the thumb and forefinger, then squeezed together along a linear track.

A recent study characterized the force JND of the human hand using an adaptive psychophysical procedure [15], similar to the approach we follow in the present study. Vicentini et al. concentrated on the measurement of the hand force and torque JNDs for usage in teleoperating a surgeon robot. They did not explicitly control with which joint the actual movement was performed and reported JNDs around 15 percent for forces bigger than 3 N. Another study considering force discrimination of the hand for communication suggested an influence of movement velocity on the JND [14]: thresholds increased with increasing velocity. The driver's perception of steering feel was measured in [16]. The method of *three-up one-down* from [25] was used setting the perception threshold to 79.4 percent. They calculated the force Weber Fractions between 11.5 and 16.5 percent.

A study investigating arm force capabilities was conducted by Tan et al. [2] reporting very low JNDs for wrist, elbow, and shoulder of 1 percent or 2 percent. Here, the force resolution was derived from a task where subjects had to track half of the maximum controllable force recorded earlier while they received the visual feedback of the applied force. The JNDs obtained here were surprisingly low and, so far, not supported by studies using classical psychophysical paradigms for measurement of the JND. Several reasons may contribute to these differences: In the experiment by Tan et al., subjects could use visual and haptic modalities to solve the task and force adjustments were performed continuously in each trial. Furthermore, the results were based on the output force of the subject instead of the input force, and the JNDs were calculated by averaging the differences between the desired and real output forces.

Another study investigated human force matching in [13]. Eight different reference forces were exerted to the left hand of subjects, and they were asked to generate an

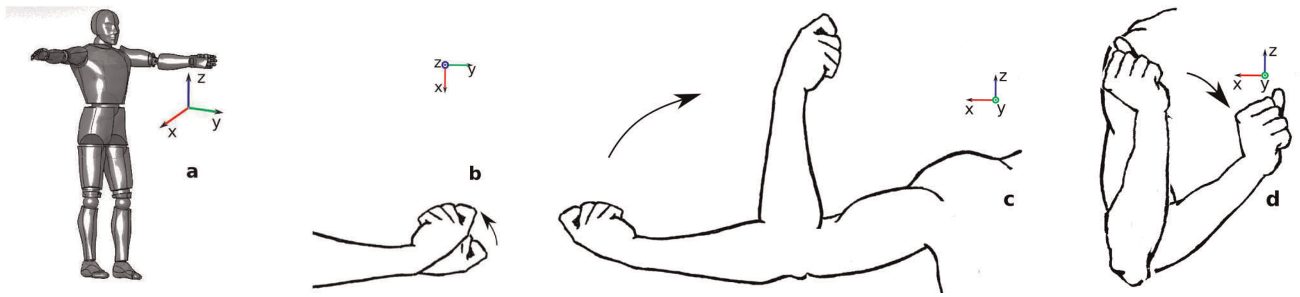

Fig. 2. Selected movements: (a) Reference frame of human body. (b) Right wrist movement from top view. (c) Right elbow movement from front view. (d) Right shoulder rotation from front view.

isometric force by their right elbow flexor muscles. A digital meter provided subjects with the feedback of their force. Weber Fractions from 5.2 to 8.8 percent (mean 7.3 percent) were obtained. In addition, studies on force discrimination capabilities of other body parts have been conducted. For the foot, for example, much higher JNDs have been reported: a study using a yes-no paradigm to improve the gas pedal system of cars considering different frequencies and footwears [17] reported JNDs between 30 and 50 percent.

In summary, force discrimination capabilities of the human arm have only been studied for subparts of the arm using specific tasks or without defining a specific movement. None of the mentioned studies combined a well-defined reproducible movement with a measurement of all possible joints of the whole arm namely the wrist, the elbow, and the shoulder. These three points are also the main force feedback points of the human arm in the application, as shown in Fig. 1. Furthermore, the methods applied in existing studies are diverse and often biased in the subjects' response. The results of a yes-no paradigm, for example, are not independent of the subject's decision criterion, so the obtained JNDs might be biased. This particular kind of bias can be avoided by using a 2-alternative forced choice (2AFC) design, where both alternatives are presented on every trial [26], [27], [28].

With the present study, we try to fill the existing gap in the literature using a controlled and a simple movement in each condition for each joint of the human arm. For the threshold measurement, we use an adaptive psychophysical measurement and a rather unbiased 2AFC design [26], [27], similar to Vicentini et al. [15] measuring force sensitivity in the hand. We apply Weber's law on multiple psychophysical thresholds (JNDs) to find the appropriate Weber Fraction with respect to the joint. The results will serve the improvement of teleoperation because the human user will receive appropriate force feedback and, thus, be able to better react to the situation at hand. In the following section, we provide more details about our approach.

3 Method and Experiments

For the development of the exoskeleton, we measured the three main contact points with the limb, where it will be possible to display the forces: wrist, elbow, and shoulder. To this aim, we measured the force discrimination abilities of the human arm relative to these locations.

3.1 Subjects

The exoskeleton was designed to fit the body size of 95 percentile of European male subjects (based on standard DIN 33402). Therefore, 10 male subjects participated in the experiment. They were right handed and reported no history of disorders concerning muscles or sense of touch. All subjects were researchers at DFKI GmbH, Robotics Innovation Center, aged between 20 and 38 years (mean 29.5, standard deviation 5.06). Each subject was informed about the purpose of the experiment, participated voluntarily, and did not get paid. The study was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). After recording, one subject had to be rejected due to inconsistent behavior (see Section 4).

3.2 Selected Movements

This section will briefly describe the selected movements and the main muscles involved. For each of the exoskeleton's contact points, we considered a corresponding movement as the reference movement, which was a typical movement during a fine-manipulation scenario (see supplementary video, available online). As null pose we assumed the limb relaxed and stretched along the body (maximal loose-packed position). A summary of all movements is given in Fig. 2. During the actual experiment, subjects had to perform each movement against a defined force (see Section 3.4).

3.2.1 Wrist Movement

Most fine manipulations with the hand will rely heavily on the movement of the wrist to place the hand and fingers accordingly. The movement selected here is a simple flexion of the wrist between -45 and $+45$ degree (Fig. 2b). The forearm muscles are made up of 19 individual units that are localized on the palmar (flexor muscles) and on the radial side (extensor muscles). Of these, the flexion of the wrist involves about six muscles [29]. Anatomically, the wrist is a colloquial term and describes the joint between the forearm and proximal carpal, radiocarpal joint, and the joint between the proximal and the distal row of the carpal bones [30]. The radiocarpal joint is functionally considered as an ellipsoidal joint and allows, among other things, flexion of the palmar extension of the dorsum of the hand.

3.2.2 Elbow Movement

For the elbow, a flexion movement between $+20$ and $+80$ degree has been selected too (see Fig. 2c). In this

TABLE 2
Phantom Omni Properties

Property	Value
Degrees of freedom	6
Force feedback along	x, y, z
Max exertable force in nominal pos	3.3 N
Force feedback workspace	160Wx120Hx70D mm
Nominal position resolution	0.055 mm

movement, only two muscles are involved: the Biceps Brachii and the Brachioradialis [30]. The elbow is like a hinge joint between humerus and ulna.

3.2.3 Shoulder Movement

In contrast to the other two joints, the shoulder movement is a rotation of the upper arm between -40 and $+40$ degree. This means that the shoulder girdle is fixed while the arm moves as depicted in Fig. 2d. The actual rotation takes place in the transverse plane around the longitudinal axis of the joint. In the movement, nine muscles are involved: Pectoralis, Serratus anterior, Rhomboideus, Latissimus, Trapezius, and muscles composing the rotator cuff [30].

3.3 Experimental Setup

The forces applied during the experiment were generated by a haptic device, *Phantom Omni*, developed by *Sensable*.[1] Its main features are summarized in Table 2. As our goal is to measure maximum sensitivity of human force discrimination, we were interested in rather small forces. Here, ΔF must be small, and we measure the force in a limited range, which is crucial for the validity of Weber's law. Accordingly, the maximum exertable force of the Phantom was sufficient for our needs (see Section 3.4).

3.3.1 Calibration and Control of Phantom

To reach high accuracy in measuring the JND and the absolute threshold, our experimental setup required precise control of the amount of force delivered to the subjects. To this end, a calibration of the haptic interface was performed before the experiments to decrease the discrepancies between the desired and the applied force. Different forces were generated by the Phantom in the xy-plane and measured by an external sensor with a resolution of 0.001 N. The resulting points were fitted using a linear regression (see Fig. 3). Finally, the calibration curve was integrated in the control system of the device. All the software was developed in C++ and was based on the Phantom driver-library that is a part of the Robot Operating System (ROS) framework (further details can be found in the webpage[2]).

3.3.2 Setup

Due to the fact that the Phantom Omni is a lightweight haptic device, different precautions were taken to prevent any unwanted motion of the limb from altering the position of the device relative to the subject. More precisely, it was necessary to setup the experiments in a way that the hand's

1. http:// www.sensable.com accessed 31 May 2012.
2. http://www.ros.org/browse/details.php?name=phantom_omni accessed 31 May 2012.

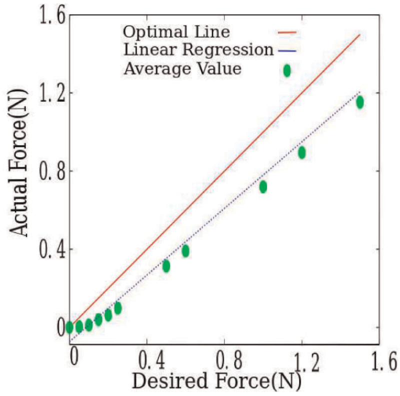

Fig. 3. Calibration diagram of Phantom in xy-plane: Green points denote average values of measured forces. The blue dotted line is computed by linearizing the average points, and the red solid line is the desired line.

trajectories were always confined within the system's workspace. The experimental setup for each movement kind is illustrated in Fig. 4.

Regarding the wrist movement a special structure was built to block the forearm of the subject. With this support, controlled movement of the wrist were easily possible.

For the elbow and the shoulder movements, we used an anti-slip mat where the subject was able to rest his arm. During the experiment the subject was asked to keep always the contact of his elbow with the table; this allowed only the movement under study. Furthermore, because only low forces were applied, no additional fixations were necessary here.

3.4 Task and Procedure

3.4.1 Experimental Procedure

Each movement type (see Section 3.2) was tested on a separate experimental day. All subjects started with the shoulder movement on day 1, continued with the wrist movement on day 2, and finished the whole experiment with the elbow movement on day 3. Each day consisted of four experimental runs, i.e., an absolute threshold measurement ($F_{ref} = 0$), and three JND measurements corresponding to three different reference forces F_{ref} (compare (2)). These reference forces were chosen such that they are much higher than the absolute threshold to avoid nonlinear effects of the Weber Fraction near the absolute threshold [13], [17]. On the other hand, we are mainly interested in force feedback during fine manipulations, so we chose rather small reference forces, i.e., 0.5, 1.0, and 1.5 N for the wrist and shoulder. For the elbow, we had to choose even smaller forces, because applying 1.5 N along the z-axis harmed the Phantom device. Therefore, we chose 0.5, 0.75, and 1.0 N as values for F_{ref}. Half of the subjects performed these runs with ascending reference forces while for the others it was descending. The weight of Phantom's arm was always compensated, i.e., without external force the arm did not move.

On each experimental day, before starting the experiment, the task was explained and the subject could perform a training run. This training was the same as an experimental run in the main experiment (see Sections 3.4.2 and 3.4.3): force differences ΔF decreased, and the training

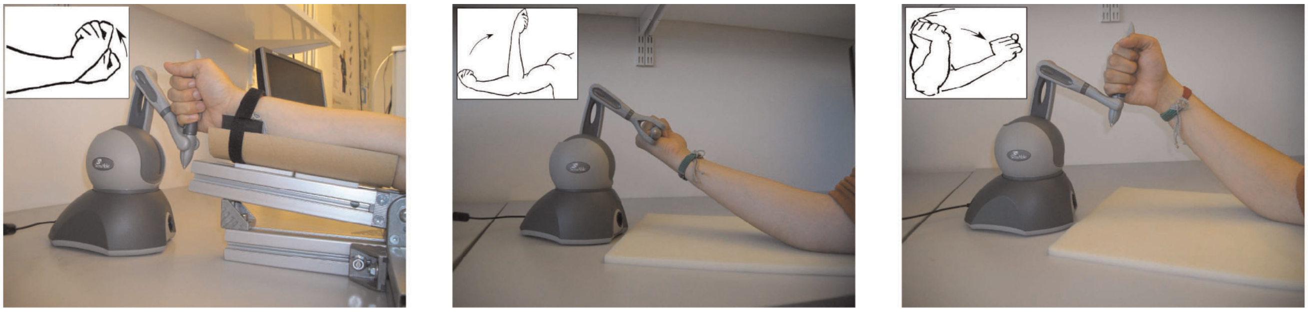

Fig. 4. Experimental setup. Left: Wrist. Middle: Elbow. Right: Shoulder.

was aborted when the subject started to make errors, i.e., when the difference was too small. For this, roughly 20 trials were needed and then the training was finished.

3.4.2 Task

For the results reported here, we used a 2AFC design, which is rather unbiased of the subject's decision criterion [26], [27]. The subject was asked to keep the end-effector of the Phantom in his right hand as shown in the Fig. 4. A defined force was applied, opposite to the direction of the expected movement, which was one of the reference forces (see Section 3.4.1) and the subject performed the intended movement (either wrist, elbow or shoulder). In the middle of the movement, for example, flexion of the wrist, the applied force either decreased or increased in the amount ΔF determined by the adaptive threshold algorithm described in Section 3.4.3. After the movement, the subject had to respond whether there was a decrease or increase in force. After each such trial, the subject was informed about the correctness of his response. For each run, i.e., for each reference force, 70 trials were performed.

3.4.3 Adaptive Threshold Measurement

The measurement of the perceptual threshold was performed with the help of the adaptive staircase procedure *QUEST* [31]. This algorithm estimates and directly tests the intended point of the psychometric function. This function is the relationship between the stimulus intensity and correct responses [28]. In other words, the value ΔF applied in a trial is the threshold actually estimated by QUEST. The next value ΔF is then estimated by QUEST according to the subject's response. With this procedure, QUEST converges to the intended intensity/performance pair.

In the current study, we used the QUEST algorithm provided by the *Psychophysics Toolbox*[3] as a Toolbox for the Matlab Software (*Mathworks Inc., Massachusetts*). In our experiments, we chose a threshold of 75 percent as the perceptual threshold, corresponding to the turning point of the psychometric function between guessing probability (50 percent) and a perfect performance (100 percent) in a 2AFC task. Other initial parameters were: threshold estimate $= 0.5$; estimated standard deviation = 0.3; Weibull function parameters: beta $= 3.5$, delta $= 0.01$, gamma $= 0.5$; step size $= 0.01$; difference range $= 1$; max value $= 0.9$; min value $= 0.01$.

3. http://psychtoolbox.org/HomePage accessed 31 May 2012.

Whether the force F_{ref} is indeed increased or decreased by ΔF is randomized during the run. The same is true for the measurement of the absolute threshold, where $F_{ref} = 0$. We took the last ΔF provided by QUEST after 70 trials as the estimated threshold for a JND specific for F_{ref} with which the Weber Fraction c can be principally determined in (1).

3.5 Data Analysis

3.5.1 Linear Regression for Weber Fraction

Weber's law describes a linear relationship between the ratio of F_{ref} and ΔF, which is still widely used in the literature as described in Section 2. To reduce noise in the threshold measurement and have enough data points for an appropriate estimate of the linear regression, we measured three JNDs belonging to three reference forces *plus* the absolute threshold, so that we have an estimate for $F_{ref} = 0$ using the benefit of adding a in the modification described in (2). The slope of this linear fit is the Weber Fraction giving us an estimate of the human force discriminability in each particular contact point of the exoskeleton.

3.5.2 Statistics

We compared absolute thresholds and Weber Fractions for different "movement types" (wrist, elbow, and shoulder), respectively, using repeated measures ANOVA with "movement type" as a within-subjects factor. Wherever appropriate, p-values were adjusted by Greenhouse-Geisser corrections. Pairwise comparisons were conducted by using posthoc paired t-tests. With this analysis, we evaluated whether the type of the movement affected the result of the absolute threshold and Weber Fraction, respectively. The bivariate correlation of absolute threshold measurements and JND measurements were calculated for each movement type (wrist, elbow, and shoulder) to investigate how the correlation pattern differs depending on "movement type."

4 Results

The behavior of the *QUEST* algorithm and its convergence to the intended threshold is illustrated by the example in Fig. 5. This figure further demonstrates that the algorithm reached the vicinity of the final threshold much faster than the 70 trials applied, which was observable for all measured contact points (wrist, elbow and shoulder). However, the additional trials were used to deal with possible noise in the measurement due to inconsistent behavior of the subjects

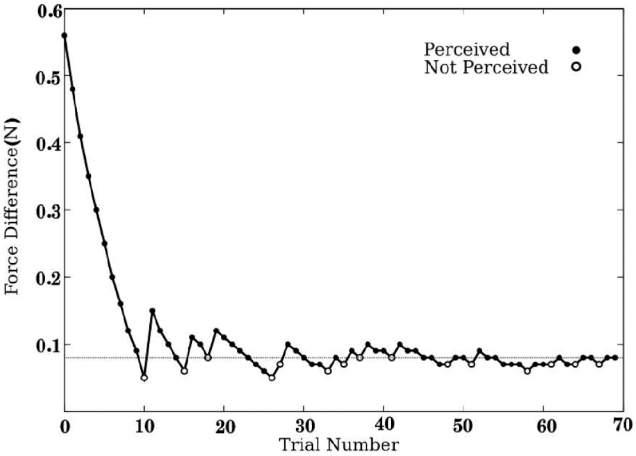

Fig. 5. Sample results taken from the shoulder movement of subject S3 with reference force of 1.0 N. Here, *QUEST* converges to 0.08.

near the threshold. This noise reduction can be seen in Fig. 5 as the curve gets smoother.

For each movement condition (wrist, elbow, and shoulder), we measured the JND for each of the three reference forces and the absolute threshold, i.e., the smallest detectable stimulus level (see also Section 2). To compute the Weber Fraction, we applied these four measurements and computed the linear regression. Then, the slope of this regression line corresponds to the Weber Fraction.

Only one subject failed in the task, which was obvious in higher values of the absolute threshold than for the JNDs tested. In the wrist task, this effect was most pronounced even causing a slightly negative slope in the linear regression (single subject results: $\Delta\phi_0 = 0.33$ N, $\Delta\phi_1 = 0.17$ N, $\Delta\phi_2 = 0.13$ N, $\Delta\phi_3 = 0.32$ N, and Weber Fraction $= -0.01$), which is in itself contradicting the results of the other subjects and the rationale behind Weber's law. For the other joints, the results were similar (elbow: $\Delta\phi_0 = 0.14$ N, $\Delta\phi_1 = 0.11$N; shoulder: $\Delta\phi_0 = 0.1$ N, $\Delta\phi_1 = 0.07$ N). For this reason, this subject was excluded from the study.

The results for all other subjects ($n = 9$) are shown in Fig. 6. The obtained averages of the Weber Fraction were 0.11 for the wrist, 0.13 for the elbow, and 0.08 for the shoulder. Absolute thresholds (mean $\pm$ standard deviation) were 0.04 ± 0.04 N for the wrist, 0.04 ± 0.04 N for the elbow and 0.04 ± 0.03 N for the shoulder. Table 3 shows the corresponding results individually for each subject as well as the median values for comparison.

TABLE 3
Absolute Thresholds and Weber Fractions Obtained for Single Subjects

	Absolute Threshold			Weber Fraction		
Subject	Wrist	Elbow	Shoulder	Wrist	Elbow	Shoulder
S1	0.03	0.04	0.05	0.11	0.10	0.09
S2	0.04	0.03	0.01	0.08	0.18	0.07
S3	0.03	0.03	0.06	0.10	0.08	0.02
S4	0.05	0.03	0.02	0.05	0.11	0.08
S5	0.03	0.05	0.04	0.09	0.14	0.11
S6	0.01	0.01	0.02	0.13	0.10	0.09
S7	0.15	0.13	0.12	0.18	0.24	0.04
S8	0.02	0.01	0.04	0.11	0.07	0.09
S9	0.03	0.01	0.01	0.16	0.16	0.12
Mean	**0.04**	**0.04**	**0.04**	**0.11**	**0.13**	**0.08**
Median	0.03	0.03	0.04	0.11	0.11	0.09
Stddev	0.04	0.04	0.03	0.04	0.05	0.03

The Weber Fraction is computed by linear regression of the single threshold measurements (three JNDs plus absolute threshold). The results are summarized in Fig. 7.

A one-factorial ANOVA for repeated measurements showed a significant main effect of "movement type" on the size of Weber Fraction [$F(2, 16) = 4.0, p < 0.05$]. However, no such main effect was revealed for the measurement of the absolute threshold [$F(2, 16) = 0.4$, $p = 0.70$]. Posthoc t-tests revealed that the pattern of Weber Fraction measurements between the wrist and the elbow movement was very similar [wrist versus elbow: $p = 0.28$]. However, the shoulder movement seemed to be different from the other movement types, which was obvious for the difference between shoulder and elbow movement [$p < 0.047$] and rather weak for the difference between shoulder and wrist [$p = 0.09$]. These differences are also obvious as regards the single subject results, as depicted in Fig. 7. The subjects behaved very similarly concerning the wrist and the elbow movement, and differently regarding the shoulder movement.

This result is underlined by the correlation analysis summarized in Table 4. For wrist and elbow movements, respectively, the measures were highly correlated (coefficients $\geq$0.75), and for each of the two conditions very homogeneous coefficients were obtained. In contrast, most measurements in the shoulder condition were rather weakly correlated or even uncorrelated and we obtained an overall heterogeneous correlation measure. This heterogeneity in the shoulder movements can also be inferred from Fig. 7: Although the measured JND generally increases with increasing reference force, the individual characteristics differ across subjects.

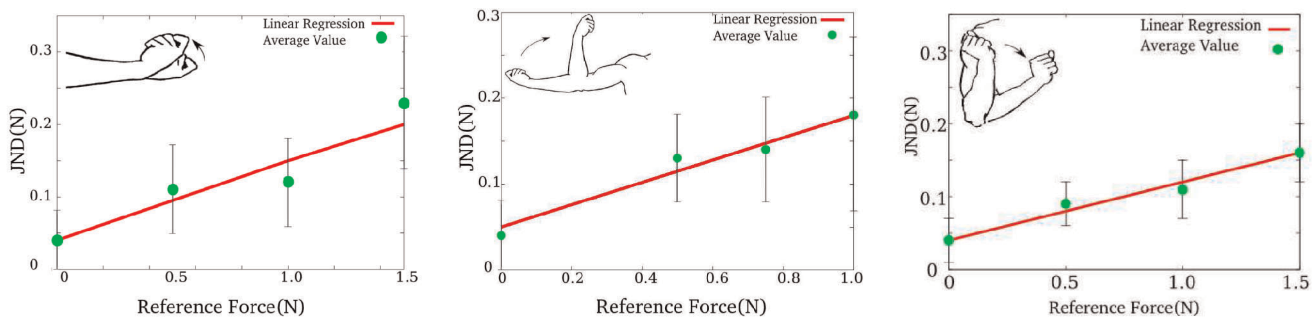

Fig. 6. Results of linear regression. Left: Wrist analysis. Middle: Elbow analysis. Right: Shoulder analysis.

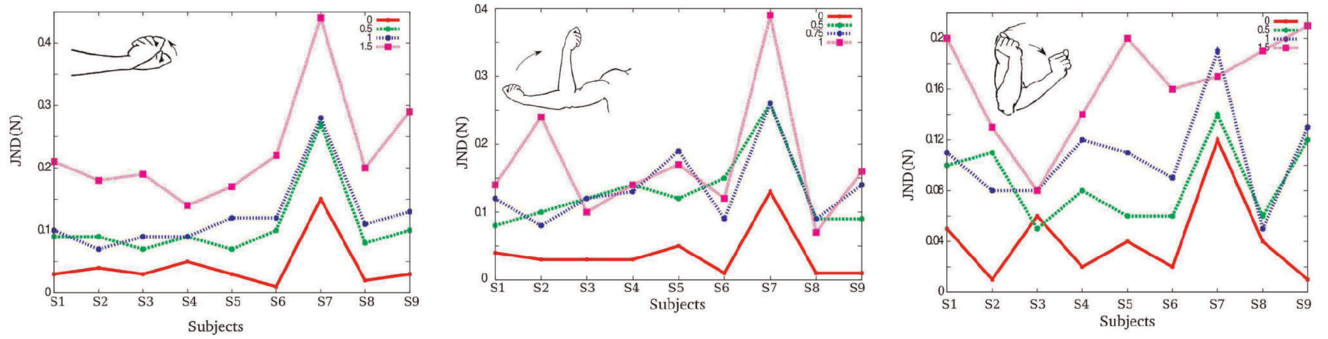

Fig. 7. Detailed JND experiments results. Each colored line represents an experiment with a particular reference force. Left: Wrist. Middle: Elbow. Right: Shoulder.

5 Discussion

The aim of this study was to analyze human arm force discrimination abilities in motion to be used in robot teleoperation using a wearable exoskeleton. For this, we measured the JNDs in the three main joints of the human arm, which correspond to the contact points of the exoskeleton. Using established psychophysical techniques, we found different force discrimination abilities in each joint demonstrating that this ability is not equally distributed across the whole arm. Therefore, our results indicate that knowledge about the force discriminability in one joint is not easily transferable to another joint in the human arm.

The magnitude of the thresholds we measured (wrist 0.11, elbow 0.13, shoulder 0.08) is comparable to the thresholds reported in the existing literature (compare Table 1), although a single study for these three joints using one well-defined movement and a response-bias free paradigm is not existing. Moreover, a direct comparison with the existing literature is almost impossible due to a high diversity of experimental approaches as described in Section 2.

We try to fill this gap here measuring the response in well-defined active movements for the whole arm using three rather low reference forces plus the absolute threshold to obtain an accurate measure of the Weber Fraction. To weaken a possible response bias due to influence of the subject's decision criterion, threshold measurements were performed with a 2AFC task, where both alternatives were presented for each trial (for details on this issue see [27, pp. 166-179]).

The study most similar to our approach is the study by Vicentini et al. [15], where much higher forces were tested for the hand and slightly higher JNDs of 15 percent were obtained. The slight difference with their results is consistent with the notion that Weber's law is only true within a limited range of reference intensities of the stimulus considered. Similar deviations have been shown for other modalities, as elucidated in Section 2.

TABLE 4
Correlation Coefficients

	Wrist	Elbow	Shoulder
$\Delta\phi_0$ and $\Delta\phi_1$	0.94	0.83	0.30
$\Delta\phi_0$ and $\Delta\phi_2$	0.87	0.88	0.58
$\Delta\phi_0$ and $\Delta\phi_3$	0.80	0.87	-0.05
$\Delta\phi_1$ and $\Delta\phi_2$	0.95	0.75	0.73
$\Delta\phi_1$ and $\Delta\phi_3$	0.92	0.76	0.30
$\Delta\phi_2$ and $\Delta\phi_3$	0.93	0.73	0.24

$\Delta\phi_0$ is the absolute threshold and $\Delta\phi_i$ the JND with respect to reference force i.

The different thresholds measured for the wrist, elbow, and shoulder might be partly explained by the number of muscles involved in the corresponding movements (see Section 3.2). According to our results, a higher number of muscles involved increases the ability to discriminate forces. This is supported by the fact that more muscles go along with more proprioception, but we cannot prove this with the current approach and such a relation remains to be shown.

In a further analysis, we investigated how the complexity of each movement affects the correlation of the results. The shoulder movement is the most complex one, and it might be performed slightly different each trial. Such differences might explain the rather low and heterogeneous correlation coefficients shown in Table 4. For elbow and wrist much higher and more homogeneous correlation coefficients were obtained. Our results indicate that a measure of correlation, like the one applied here, can be used as an overall indicator of the reproducibility of the results with respect to the movement applied.

5.1.1 Linear Regression

Since the Weber Fraction is actually the slope of a linear relationship between $\Delta\phi_i$ and ϕ_i (compare (2)), we decided to compute it using the linear regression approach. Given that the reference forces chosen for measuring the JND do not exceedingly differ in their magnitude, the proportion of the obtained JND should be more or less the same according to Weber's law. In addition to the fact that we reduce the estimation noise by obtaining three points for the linear regression, we used the extension of adding a fourth value for taking into account an offset at ϕ_0 [8]. In summary, we used four independent measurements to estimate the Weber Fraction postulated in Weber's law.

This effect of a linear relationship between measured perceptual thresholds across subjects is also supported by the results of the correlation analysis for the wrist and the elbow movement. For these movements, we obtained similar patterns of thresholds for all subjects, i.e., when a subject had a higher JND for ϕ_1 the JND for ϕ_2 was very likely to be high as well. For the shoulder movement, this correlation was not observed, which might be attributed to the higher flexibility in the movement itself, as discussed above. Nevertheless, we reliably measured the increase in JND with increasing reference force as predicted by Weber's law (compare Figs. 6 and 7).

5.1.2 Behavioral Measurements

From the 10 subjects that originally took part in the experiment we had to reject the results of one subject due to inconsistent behavior in the experiment (see Section 4). The results for the remaining nine subjects were in agreement with Weber's law, but still contained a lot of noise as can be drawn from the individual results (Fig. 7). There is not always a distinct gradient of JND obtained from lowest to highest reference force. Furthermore, not all subjects are equal in their sensitivity, for example, S7 needed higher amounts of force to respond.

According to the methods applied in this study, our results are rather free of individual response biases, but still many error sources remain in the final setup. First of all, the measurement itself is not noise free. The psychophysical threshold is a well-known and often used concept, but its identification is always difficult: Fast and at the same time completely bias-free methods are not existing. A more accurate measure needs more time, for example, by recording many more trials using the Method of Constant Stimuli [28] in the vicinity of the threshold, with the drawback of introducing new noise by exhausting subjects. Second, there is always the problem that measurement noise adds with possible noise from the recording device. To maximally reduce this factor, we applied an extra calibration procedure prior to the experiment. Still, due to the sigmoid shape of the psychometric function, even small changes of stimulus intensity influence the performance in the vicinity of the threshold. Therefore, if the Phantom device is imprecise at that point, the accuracy of the threshold estimate will be influenced. Third, there is a certain degree of flexibility in every movement. Although we tried to counteract this using simple experimental manipulations, there is always some flexibility remaining. Indirectly, we demonstrate this effect for the shoulder movement, where we lose the correlation of the results across subjects. It is straightforward that slight changes in the movement also slightly change the way the corresponding muscles are involved, which may in turn change proprioception.

However, our aim was to have a simple and at the same time reliable estimation of the force discrimination abilities of humans when conducting arm movements. Although we had to face all the difficulties stated above, we could show that a measurement of these thresholds is possible and reliable across subjects. This is supported by the quality of the linear regression and indirectly by the correlation analysis for the wrist and the elbow movement. Concerning the quality of the results, the accuracy obtained should be sufficient for the final application as discussed in the following paragraph.

5.1.3 Transfer to Application

The results of the present study will be used as requirements for the construction of a wearable exoskeleton. In particular, they will help in defining the accuracy that is needed in the actuation system to display a proper force feedback. In a normal teleoperation scenario the force feedback will be exerted to the user's arm in dynamic conditions. This is in accordance with our experiments that were intended to analyze the force sensitivity of different parts of the human arm during motion. The active movements in our sets of experiments simulate a dynamic teleoperation scenario.

For the measurement of the absolute threshold, we would like to point out that the friction still remains in the system. This friction can be considered as a static force, which also exists in the final scenario with the exoskeleton. According to experience with previous exoskeletons, we would hypothesize that the user gets used to this friction after some time, and will consider it as a part of his arm. This will be investigated in the final system.

6 Conclusions and Future Works

In this study, we characterized human perception of external forces for all three main joints of the human arm, i.e., wrist, elbow and shoulder. We showed that this can be done by applying psychophysical procedures, as long as these are independent of individual response biases. Although we could reliably measure thresholds for force perception, our results demonstrated that these thresholds were different for the joint with which the movement was performed. With the approach presented here of characterizing the perceptual threshold for each joint separately, we are able to complement existing studies (such as [15]), which considered the arm as one single structure (all joints are equal) when measuring the force JND. Furthermore, we suggested simple correlation measurements as indicators for the robustness of the movement under study. Other possible influences, like movement velocity and direction, were beyond the scope of the present study, but could be investigated using the same methodology.

We summarized the results obtained using the Weber Fraction as the key value for the force discrimination ability of each joint. For the application, an exoskeleton used for teleoperation, the Weber Fraction will be used to design the system with proper actuators and adjust the feedback delivered to the human appropriately via a specific mapping between the teleoperated robot and the exoskeleton. This, for example, will be required when the teleoperated robot is able to detect forces with a higher precision in comparison to the human arm.

In the application, the respective force JND can be considered during teleoperation and it will be interesting to see how much this will improve the human abilities using the system. However, in some situations in the scenario, forces will be applied to more than one joint at a time. This might in turn change the overall sensitivity of human perception in that particular situation. The final effect of this can only be estimated in the final system, where we can measure the force combination effect.

In the present paper, we raised the idea about the influence of the number of involved muscles in a movement on force sensitivity. This idea may be validated in the future. One proposition for this would be to analyze the EMG signals and evaluate possible dependencies with the subjects' force discrimination abilities.

Acknowledgments

This work was supported by the German Bundesministerium für Bildung und Forschung (BMBF, grant FKZ 01IW10001). The help of Foad Ghaderi is highly appreciated in reviewing the paper. The authors are pleased to thank Niels Will for his scientific support. They would also like to thank all the people who took part in the experimental phase.

References

[1] M. Monroy, M. Oyarzabal, M. Ferre, A. Campos, and J. Barrio, "MasterFinger: Multi-Finger Haptic Interface for Collaborative Environments," *Proc. Haptics: Perception, Devices and Scenarios,* pp. 411-419, 2008.

[2] H. Tan, J. Radcliffe, B.N. Ga, H.Z. Tan, B. Eberman, M.A. Srinivasan, and B. Cheng, "Human Factors for the Design of Force-Reflecting Haptic Interfaces," *Proc. Third Int'l Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems,* 1994.

[3] F. Barbagli, K. Salisbury, C. Ho, C. Spence, and H.Z. Tan, "Haptic Discrimination of Force Direction and the Influence of Visual Information," *ACM Trans. Applied Perception,* vol. 3, pp. 125-135, Apr. 2006.

[4] M.K. O'Malley and A. Gupta, "Haptic Interfaces," *HCI: Beyond the GUI,* pp. 25-74, Morgan Kaufmann, 2008.

[5] M. Folgheraiter, B. Bongardt, S. Schmidt, J. de Gea Fernandéz, J. Albiez, and F. Kirchner, "Design of an Arm Exoskeleton Using a Hybrid Motion-Capture and Model-Based Technique," *Proc. IEEE Int'l Conf. Robotics and Automation (ICRA '09),* May 2009.

[6] M. Folgheraiter, B. Bongardt, J. Albiez, and F. Kirchner, "A Bio-Inspired Haptic Interface for Tele-Robotics Applications," *Proc. IEEE Int'l Conf. Robotics and Biomemetics (ROBIO '08),* Dec. 2008.

[7] C. Ericson, *Real-Time Collision Detection.* Morgan Kaufmann, 2004.

[8] T.A. Kern, "Biological Basics of Haptic Perception," *Engineering Haptic Devices,* pp. 35-58, Springer, 2009.

[9] C. Doerrer and R. Werthschuetzky, "Simulating Push-Buttons Using a Haptic Display: Requirements on Force Resolution and Force-Displacement Curve," *Proc. EuroHaptics,* May 2002.

[10] S. Allin, Y. Matsuoka, and R.L. Klatzky, "Measuring Just Noticeable Differences for Haptic Force Feedback: Implications for Rehabilitation," *Proc. Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems,* pp. 299-302, http://computer.org/proceedings/haptics/1489/14890299abs.htm, 2002.

[11] B. Brewer, M. Fagan, R. Klatzky, and Y. Matsuoka, "Perceptual Limits for a Robotic Rehabilitation Environment Using Visual Feedback Distortion," *IEEE Trans. Neural Systems and Rehabilitation Eng.,* vol. 13, no. 1, pp. 1-11, Mar. 2005.

[12] X. Pang, H. Tan, and N. Durlach, "Manual Discrimination of Force Using Active Finger Motion," *Attention, Perception, & Psychophysics,* vol. 49, pp. 531-540, http://dx.doi.org/10.3758/BF03212187, 1991.

[13] L. Jones, "Matching Forces: Constant Errors and Differential Thresholds," *Perception,* vol. 18, no. 5, pp. 681-687, 1989.

[14] M. HosseiniZadeh, D. Wang, and E. Kubica, "Perception-Based Lossy Haptic Compression Considerations for Velocity-Based Interactions," *Multimedia Systems,* vol. 13, no. 4, pp. 275-282, http://dx.doi.org/10.1007/s00530-007-0106-9, 2008.

[15] M. Vicentini, S. Galvan, D. Botturi, and P. Fiorini, "Evaluation of Force and Torque Magnitude Discrimination Thresholds on the Human Hand-Arm System," *ACM Trans. Applied Perception,* vol. 8, no. 1, article 1, 2010.

[16] A.C. Newberry, M.J. Griffin, and M. Dowson, "Driver Perception of Steering Feel," *Proc. Institution of Mechanical Engineers Part D-J. Automobile Eng.,* vol. 221, no. D4, pp. 405-415, Apr. 2007.

[17] D.A. Abbink and F.C.T. van der Helm, "Force Perception Measurements at the Foot," *Proc. IEEE Int'l Conf. Systems, Man and Cybernetics,* pp. 2525-2529, 2004.

[18] G.T. Fechner, *Elemente der Psychophysik.* Breitkopf und Hrtel, 1860.

[19] M. Aguilar and W.S. Stiles, "Saturation of the Rod Mechanism of the Retina at High Levels of Stimulation," *Optica Acta,* vol. 1, pp. 59-65, Jan. 1954.

[20] R.P. Carlyon and B.C. Moore, "Intensity Discrimination: A Severe Departure from Weber's Law," *J Acoustic Soc. Am.,* vol. 76, no. 5, pp. 1369-1376, Nov. 1984.

[21] N.B. Debats, I. Kingma, P.J. Beek, and J.B.J. Smeets, "Moving the Weber Fraction: The Perceptual Precision for Moment of Inertia Increases with Exploration Force," *PLoS One,* vol. 7, no. 9, article e42941, 2012.

[22] E. Francisco, V. Tannan, Z. Zhang, J. Holden, and M. Tommerdahl, "Vibrotactile Amplitude Discrimination Capacity Parallels Magnitude Changes in Somatosensory Cortex and Follows Weber's Law," *Experimental Brain Research,* vol. 191, no. 1, pp. 49-56, 2008.

[23] J. SmurzyÅski and A.J. Houtsma, "Auditory Discrimination of Tone-Pulse Onsets," *Perception Psychophysics,* vol. 45, no. 1, pp. 2-9, 1989.

[24] R.S. Moyer and T.K. Landauer, "Time Required for Judgements of Numerical Inequality," *Nature,* vol. 215, no. 5109, pp. 1519-1520, 1967.

[25] G. Wetherill and H. Levitt, "Sequential Estimation of Points on a Psychometric Function," *British J. Math. and Statistical Psychology,* vol. 18, no. 1, pp. 1-10, 1965.

[26] D.M. Green and J.A. Swets, *Signal Detection Theory and Psychophysics.* Peninsula Publishers, 1988.

[27] N.A. Macmillan and C.D. Creelman, *Detection Theory : A User's Guide.* Lawrence Erlbaum, 2005.

[28] W.H. Ehrenstein and A. Ehrenstein, "Psychophysical Methods," *Modern Techniques in Neuroscience Research,* pp. 1211-1241, Springer, 1999.

[29] K. Zilles and B.N. Tillmann, *Anatomie.* Springer-Verlag, 2010.

[30] I.A. Kapandji and J. Koebke, *Funktionelle Anatomie Der Gelenke. Schematisierte Und Kommentierte Zeichnungen Zur Menschlichen Biomechanik.* Georg Thieme Verlag, 2006.

[31] A. Watson and D. Pelli, "Quest - A Bayesian Adaptive Psychometric Methods," *Perception and Psychophysics,* vol. 33, no. 2, pp. 113-120, 1983.

Seyedshams Feyzabadi studied computer engineering from the Iran University of Science and Technology from 2002 to 2007. After receiving a full scholarship from Jacobs University Bremen, he continued his studies in computer science. He received the master's degree in 2010, focusing on robotics systems. He has been a researcher at the Robotics Innovation Center at the German Research Center for Artificial Intelligence since 2010. He has been involved in VI-Bot, single arm active exoskeleton, and CAPIO, dual arm active exoskeleton, projects. His primary interests include robot teleoperation and human-robot-interaction.

Sirko Straube received the diploma in biology in 2005 from the Albert-Ludwigs-University Freiburg, Germany, and the Dr. rer nat in 2009 from the University of Bremen, Germany. Since 2005, he has been a researcher in the Department of Human Neurobiology at the University of Bremen. Beginning in 2009, he was a postdoctoral researcher with the AG Computational Neuroscience at the Carl-von-Ossietzky-University Oldenburg, Germany. Since 2010, he has been a postdoctoral researcher at the Robotics Lab, University of Bremen. His area of interests comprises of signal processing, neurophysiological methods, psychophysics, and human-machine interfacing.

Michele Folgheraiter received the MS degree in computer science with major in automation systems and the PhD degree in computer science from Politecnico di Milano University, in 2000 and 2004, respectively. From 2002 to 2007, he held the positions of contract researcher and teaching assistant in Robotics-1 and Robotics-2 classes at Politecnico di Milano. Since 2008, he has been with the German Research Center for Artificial Intelligence as a senior researcher. His research interests focus in the areas of humanoid robotics, haptic interfaces, and bioinspired control systems.

Elsa Andrea Kirchner received the diploma in biology from the University of Bremen in 1999. From 1996 to 1999, she was on a scholarship from the Studienstiftung des deutschen Volkes and was awarded with the Stiftung Familie Klee Award for a scholarship at MIT, Boston, where she was a guest research scientist from 1999 to 2000. Since 2005, she has been a staff scientist at the Robotics Lab, University of Bremen, and since 2006, she has been a project leader at the Robotics Innovation Center of the German Research Center for Artificial Intelligence in Bremen. Her scientific interests are in the field of human-machine interfaces, cognitive architectures, neuropsychology, and electrophysiological methods.

Su Kyoung Kim received the MA degree in clinical linguistics, linguistics, and psychology in 2003 and the Dr. Phil degree in clinical linguistics in 2007, both from the University of Bielefeld, Germany. Since 2008, she has been with the Robotics Lab at the University of Bremen and the Robotics Innovation Center of the German Research Center for Artificial Intelligence in Bremen. Her scientific interests are in the field of neurolinguistics, neuropsychology, electrophysiological methods, and statistical analysis.

Jan Christian Albiez studied computer science with a specialization on robotics and processor architecture at the University of Karlsruhe, Germany, from 1993 to 1999 and received the Dr. Ing from the University of Karlsruhe for his dissertation about behavior networks for reactive control of biologically inspired walking machines in 2007. He started working as a researcher in the area of biologically inspired walking machines and immersive telerobotics at the Forschungszentrum Informatik in Karlsruhe in 2000. Since 2006, he has been a senior researcher and project leader at the Robotics Innovation Center of the German Center for Artificial Intelligence in Bremen, focusing on autonomous underwater robots and immersive teleoperation.

▹ **For more information on this or any other computing topic, please visit our Digital Library at** www.computer.org/publications/dlib.