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An evaluation of the contact forces on the fingers when squeezing a spherical rehabilitation ball

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Abstract

The rehabilitation squeeze ball is a popular device to help strengthen the hand, fingers and forearm muscles. The distributions of the contact pressure in the interface between the therapy ball and hand/fingers can affect the joint moment of each of the individual fingers, thereby affecting rehabilitation effects. In the current study, we evaluated the contact force distributions on the fingers when gripping a spherical object. Eight female adults [age 29 (9.1) years, mass 64.6 (7.1) kg, height 163.5 (1.9) cm, hand length 17.2 (0.7) cm] participated in the study. Contact force sensors were attached to the middle of the palmar surfaces of the distal, middle, and proximal phalanges of the four fingers in the longitudinal direction. In order to evaluate the effects of the ball stiffness on the contact force distributions on the fingers, subjects were requested to perform quasi-static gripping on a standard tennis ball and on a rehabilitation ball. The tennis ball is much stiffer and experiences smaller deformation under compression compared to the rehabilitation ball. We analyzed the force share among the distal, middle, and proximal finger segments, when subjects gripping balls of different stiffnesses (tennis ball vs. rehabilitation ball) and at three different grip efforts. Our results indicated that the grip force is contributed about 60% and 40% by the middle/ring fingers and by the index/little fingers, respectively. These characteristics are independent of the grip force levels and stiffness of the contact surface.

Keywords

Hand; fingers; grip; physical therapy; spherical ball

1. Introduction

Musculoskeletal disorders (MSDs) of the hand and fingers are found to be related to occupational activities in multiple industrial sectors [1]. In order to reduce the MSDs of the hand, research efforts have been put towards optimizing tool design, especially at improving the handle design. Previous studies indicate that an optimized handle can reduce both physical effort and musculoskeletal fatigue, thereby improving comfort and reducing the risk of musculoskeletal disorders. Design factors that affect the grip strength, operator's comfort, and safety have been identified, such as the diameter of the handle [2–6], the properties of

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Conflict of interest
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the covering materials [7,8], the handle shape [9–11], the friction of the surface [12], and the contact stiffness [13]; also, the posture of the operator is identified as an important factor [14]. Despite these efforts, MSDs of the upper extremity, which includes shoulder, wrist, hand, and finger, still accounted for approximately 33% of lost work day injuries in the manufacturing sector [15].

One of the effective intervention methods for the work-related hand MSDs is hand exercises and rehabilitation. Che et al. [16] did a questionnaire study on the effectiveness of hand therapy for an occupation-based intervention in Malaysia; they found that occupational therapies are effective for the occupation-based intervention and helpful for successful rehabilitation of hand injuries. Melvin [17] indicated, in a study regarding the role of the occupational therapy in hand rehabilitation in the U.S., that occupational therapy makes a major contribution to the practice and continued development of hand rehabilitation. Seu and Pasqualetto [18] investigated the role of the occupational therapies in recovering the intrinsic muscle dysfunction to regain functional use of the hand for daily activities; they indicated that occupational therapists play an important role in the rehabilitation process to regain motion, strength, and dexterity for the workers. In order for the hand rehabilitation to get more effective results, understanding of the biomechanics of the therapies would be helpful. However, there is little biomechanical analysis of the hand therapies in literature.

One of the most popular types of hand exercise and rehabilitation equipment is the hand rehabilitation or therapy ball, which is commercially widely available [e.g., Physioroom (www.physioroom.com), Rehabmart (www.rehabmart.com), and Isokinetics Inc. (www.isokineticsinc.com)]. The therapy ball is claimed to help strengthen the hand, fingers and forearm muscles and to increase the range of movement of the joints. The therapy ball is usually made of elastic silicone materials of different compression stiffness. The distributions of the contact pressure in the interface between the therapy ball and hand/fingers may affect the joint moment of each of the individual fingers, thereby affecting the distributions of the forces among the muscles. The biomechanics of grasping has been studied by several researchers previously. For example, Freund et al. [19] developed a four-finger model to investigate the dependence of the fingertip contact force on the gripping force, handle diameter, and hand size. Kargov et al. [20] analyzed the contact force and joint moment distributions for different prosthetic hand designs and the human hand when fulhlling a gripping task. Nicholas et al. [21] quantified the force distribution and contact area of the hand when gripping, pushing, and pulling a cylinder using a pressure sensor him. All of these previous studies involve the contact between the hand/fingers and a cylindrical surface. The deformation of the cylindrical surface is negligible and the cylinder is considered as rigid relative to the fingers. The approaches used in the previous studies cannot be applied to study the contact interaction between the hand/fingers and therapy ball, because the ball is usually spherical or ellipsoidal and the ball will often be subjected to large deformation when being squeezed.

The current therapy balls have not been designed based on biomechanics. The shape and stiffness could be optimized to achieve required muscle exertion of the hand. The knowledge of the contact force distributions is essential for the design of the hand therapy device on a biomechanics basis. The purpose of the current study is to quantify the distributions of the dynamic contact forces between the hand/fingers and spherical ball. The contact forces will be measured as a function of time for different grip efforts and for different stiffness of the ball. Our hypothesis is that the distribution of the contact pressure on the fingers is dependent on the grip force and the stiffness of the therapy ball.

2. Methods

Eight female adults [age 29 (9.1) years, mass 64.6 (7.1) kg, height 163.5 (1.9) cm, hand length 17.2 (0.7) cm] participated in the study, providing informed consent under a protocol approved by the Centers for Disease Control and Prevention. Hand length was measured as the distance from the proximal wrist crease to the tip of the long finger with the hand extended [22].

Contact force sensors (Pressure Profile Systems, Los Angeles, USA) were attached to the middle of the palmar surfaces of the distal, middle, and proximal phalanges of the four fingers in longitudinal direction; no sensor was attached on the thumb (Fig. 1). Each of the force sensors was individually calibrated at intervals up to 15 N using Pressure Profile System (PPS) vendor’s software. Motion capture markers (4 mm hemispheres) were applied to the hand to implement the “6DHand” six degree of freedom kinematic model [23], Three motion capture markers were attached to each of the finger/hand segments.

In order to evaluate the effects of the ball stiffness on the contact force distributions on the fingers, subjects were asked to perform a series of quasi-static gripping trials on a standard tennis ball (Fig. 1, left) and on a rehabilitation ball (Fig. 1, right). The tennis ball (65 mm diameter) has a similar dimension but a higher stiffness, compared to the rehabilitation ball (69 mm diameter). Following a kinematic calibration trial, subjects were instructed to perform gripping trials on the tennis ball and on the rehabilitation ball in a random order. Each subject first performed two maximum effort gripping tasks of approximately five seconds. The total force measured from all sensors during a quasi-static portion of each trial was averaged to calculate the subject’s maximum voluntary exertion (MAX) force value for the particular type of ball. The subject then performed four trials in a random order, two each at 50% and 25% of MAX. Subjects were shown the real-time grip force feedback on a computer monitor and were requested to target and maintain a specific grip force level. Between two subsequent trials, subjects rested for at least two minutes to recover from musculoskeletal fatigue. To begin each trial, an experimenter placed the ball in the subject’s instrumented hand. Subjects were instructed to minimize the adduction of the fingers while gripping.

Data of the PPS sensors were collected at 40 Hz. During each trial, tare offsets were collected with the sensors being unloaded, either immediately before or after the data collection of the trial; the mean of a one-second range was used to apply as a tare to the collected data for each sensor. A zero floor was thus established. The recorded force data show some variations even though the subjects were requested to maintain a constant grip force. In order to minimize the uncertainty of the test data and to obtain a reasonable mean force value for each individual sensor during the quasi-static exertion, a moving four-second range with the minimum total force variance during the exertion was identified. The mean value of each sensor was calculated across this identified range.

Using the measured forces on the finger segments, f_i^j the force share in each of the finger segments, ϕ_i^j is calculated by:

$$\phi_i^j = \frac{f_i^j}{F^j}, \quad i \in \{\text{distal, middle, proximal}\}; \qquad (1)$$

$$F^j = f_{distal}^j + f_{middle}^j + f_{proximal}^j, \quad j \in \{\text{little, ring, middle, index}\}$$

where the subscript "i" and superscript "j" imply finger segments (distal, middle, proximal) and fingers (little, ring, middle, index), respectively. F^j represents the force on the finger "j"; f_i^j and ϕ_i^j is the force and the force share, respectively, on the finger segment "i" and finger "j".

The force share in each of the fingers, Φ^j, is calculated by:

$$\Phi^j = \frac{F^j}{F^{little} + F^{ring} + F^{middle} + F^{index}}, \quad j \in \{\text{little, ring, middle, index}\}. \qquad (2)$$

where Φ^j represents the force share on the finger "j". Apparently, the force share is a ratio and has no unit.

3. Results

The force share among the distal, middle, and proximal finger segments for three grip force levels are shown in Figs 2 and 3, respectively, for gripping on tennis ball and rehabilitation squeeze ball. In the figures (Figs 2 and 3), the first, second, and third column of the plots are for the grip force levels of 25%, 50%, and 100% MAX, respectively; whereas the first, second, third, and fourth row of the plots represent the force distributions in the little, ring, middle, and index finger, respectively.

The results of the force share among fingers are plotted as a function of grip force in Fig. 4, in which the left and right column of the plots represent the tennis ball and squeeze ball grip, respectively. Our results show that, for each of the fingers, the distal finger segments share approximately 50% of the total force, whereas the proximal segments took the least force share (approximately 10%) for all grip force levels. The grip force level affects the force distributions on the finger segments, however, the general trends are not changed. A reduced ball stiffness (i.e., squeeze ball vs. tennis ball) tends to increase the force sharing of the middle segment of the middle finger, while it has little effect on the force distributions on other three fingers (Fig. 4).

The total grip forces shared by each finger as a function of the grip force level are shown in Fig. 5. The left and right column of the plots represent the results for the tennis ball grip and squeeze ball grip, respectively; the first, second, third, and fourth row of the plots are the force share of the little, ring, middle, and index finger, respectively. For the tennis ball grip, the force shares in the index and middle fingers increase with the increase of the grip force level. However, for the squeeze ball grip, there is no consistent trend for the effects of the grip force level on the force sharing on the fingers. The dependence of the grip forces shared by fingers are demonstrated more clearly in Fig. 6. Our results show that the trends of the force sharing among the fingers for both tennis ball (Fig. 6, Left) and squeeze ball grips (Fig. 6, Right) and under all force levels are consistent: the middle and ring fingers share approximately 50% more force than the other two fingers.

The force sharing characteristics on fingers are further analyzed in Figs 7,8. The effects of the grip force level on the force sharing of each individual finger are illustrated clearly in Fig. 7. For the tennis ball grip (Fig. 7, Left), the force shares in the ring and little fingers decrease while those in the middle and index fingers increase with increasing grip force level. In comparison, the grip force level has less effect on the force sharing for the squeeze ball grip (Fig. 7, Right). By comparing the force share on the index and ring fingers and on the index and little fingers (Fig. 8), it is seen that the most grip force (approximately 60%) is distributed on the index and ring fingers for all grip force levels, especially for the squeeze ball grip (Fig. 8, Right).

4. Discussion

The contact between fingers and tool handle has been studied for ergonomic design [2,5,6]. All these previous studies dealt with the contact between the fingers with cylindrical surface. The contact of the fingers with spherical objects has been scarcely studied. In the current study, we evaluated the contact force distributions on the fingers when gripping a spherical object. Our results indicated consistently that the grip force is contributed about 60% and 40% by the middle/ring fingers and by the index/little fingers, respectively. These characteristics are independent of the grip force levels and stiffness of the contact surface.

To our best knowledge, there is no published data regarding the force sharing among fingers when gripping a spherical object. The closest relevant study in literature, which we can qualitatively compare our results with, is the cylindrical grip [5]. Our results show that the contact force is concentrated most on the distal segment in each of the fingers for both tennis ball and squeeze ball grip test, independent of the grip force levels. This phenomenon is similar to those observed in the cylindrical grip tests [5], where the distal, middle, and proximal finger segment was found to share approximately 50%, 17%, and 33% of the grip force, respectively. The force share pattern among the fingers is a little different: the majority of the hand grip force is contributed by the middle and ring fingers in the spherical grip, while the hand grip force is mainly distributed on the index (about 30%) and middle (about 33%) fingers in the cylindrical grip [5].

The effects of the ball stiffness on the force sharing in the fingers and in the finger segments is likely caused by the deformation of the ball. We observed that the deformation of the tennis ball is negligible under the maximal grip whereas the aspect ratio of the squeeze ball varied from 1.0 to approximately 0.8 under the maximal grip force. The changes of the ball shape varies the kinematics of the subjects fingers, thereby varying the subjective feel and grip effects.

In the current study, we utilized the PPS sensors, which were attached on the fingers, to evaluate the forces on each of the finger segments when gripping on a spherical object. In the previous studies (e.g., [24]), the contact pressure was measured by using pressure sensor film that was wrapped on the contact surface of the object. For the current study, it is technically difficult to wrap a pressure sensor film on a spherical surface; in comparison, the application of the PPS sensors is independent of the curvature of the contact surface.

In the current study, we recruited female participants only and the variation of the subjects' hand dimensions are within 10%. The ratio of the hand size relative to the dimension of the spherical ball will likely affect the gripping behavior. The effects of the hand size and gender have not been included in our study.

The PPS finger sensors are elastic and they have to be fitted on to subjects' finger segments. Because of variations in the hand sizes among the subjects, the tightness of the PPS sensors on the fingers would be different from subject to subject. The relative position of the PPS sensors on the finger segments was visually checked and it may contain some variations. In addition, the PPS sensors may slide relative to the fingers when squeezing the rehabilitation ball, which experienced large deformation during the maximum voluntary exertion. All these factors may contribute to the measurement errors. However, despite all these factors that may cause uncertainty to our measurements, the scattering of our results is in a reasonable range.

5. Conclusion

In the current study, the distributions of the dynamic contact forces between the hand/fingers and spherical ball have been quantified. The grip force is found to be contributed about 60% and 40% by the middle/ring fingers and by the index/little fingers, respectively. These force sharing characteristics among the fingers are independent of the grip force levels and stiffness of the contact surface.

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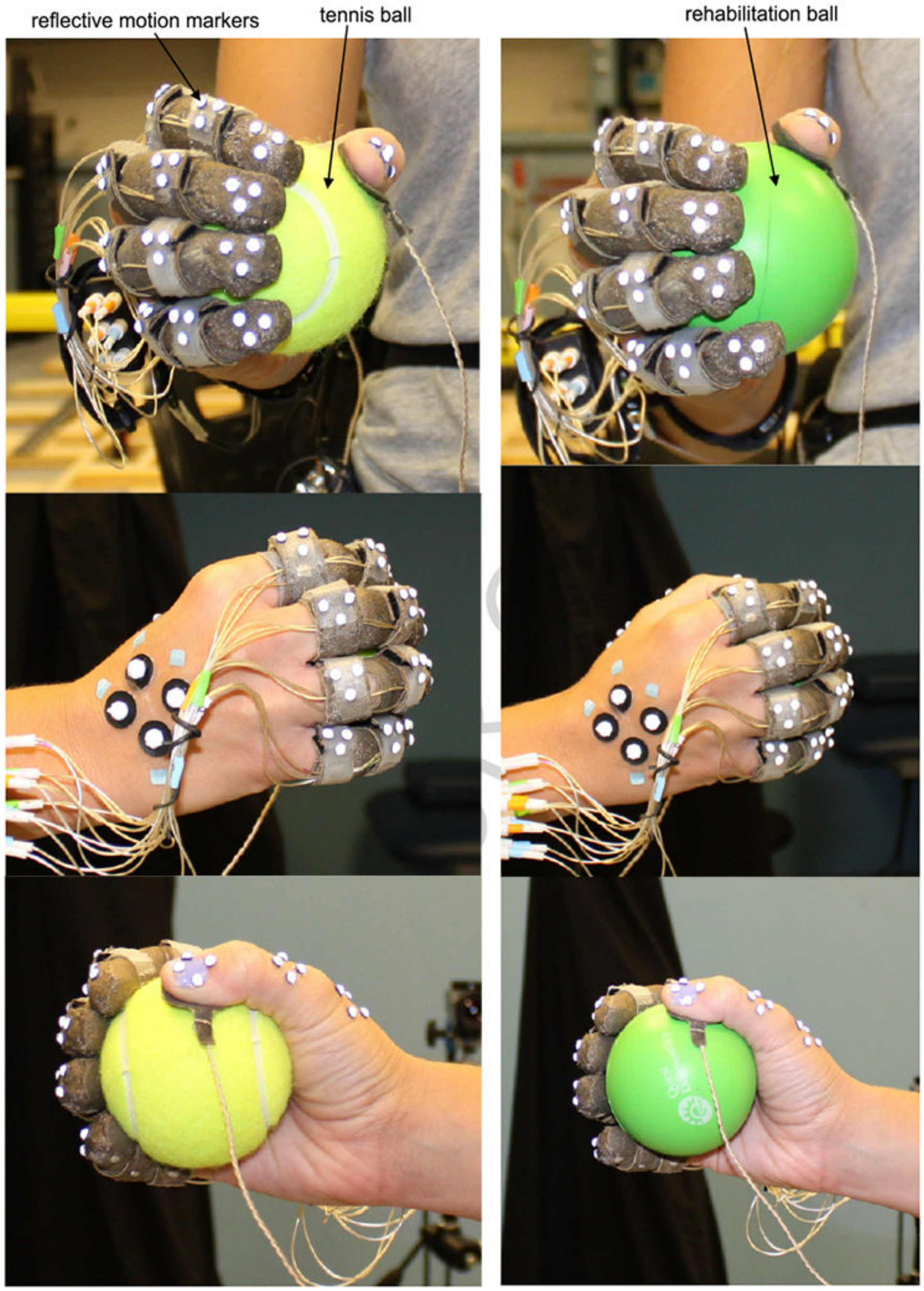


Fig. 1.

Experimental setup. Left: grip on a standard tennis ball. Right: grip on a rehabilitation ball. The tennis ball (65 mm diameter) has a similar dimension but a higher stiffness, compared to the rehabilitation ball (69 mm diameter). Contact force sensors (FingerTPS, Pressure Profile Systems. Los Angeles. USA) were attached to the middle of the palmar surfaces of the distal, middle, and proximal phalanges of the four fingers. Three motion capture makers (4 mm hemispheres) were applied on each of the finger and thumb segments.

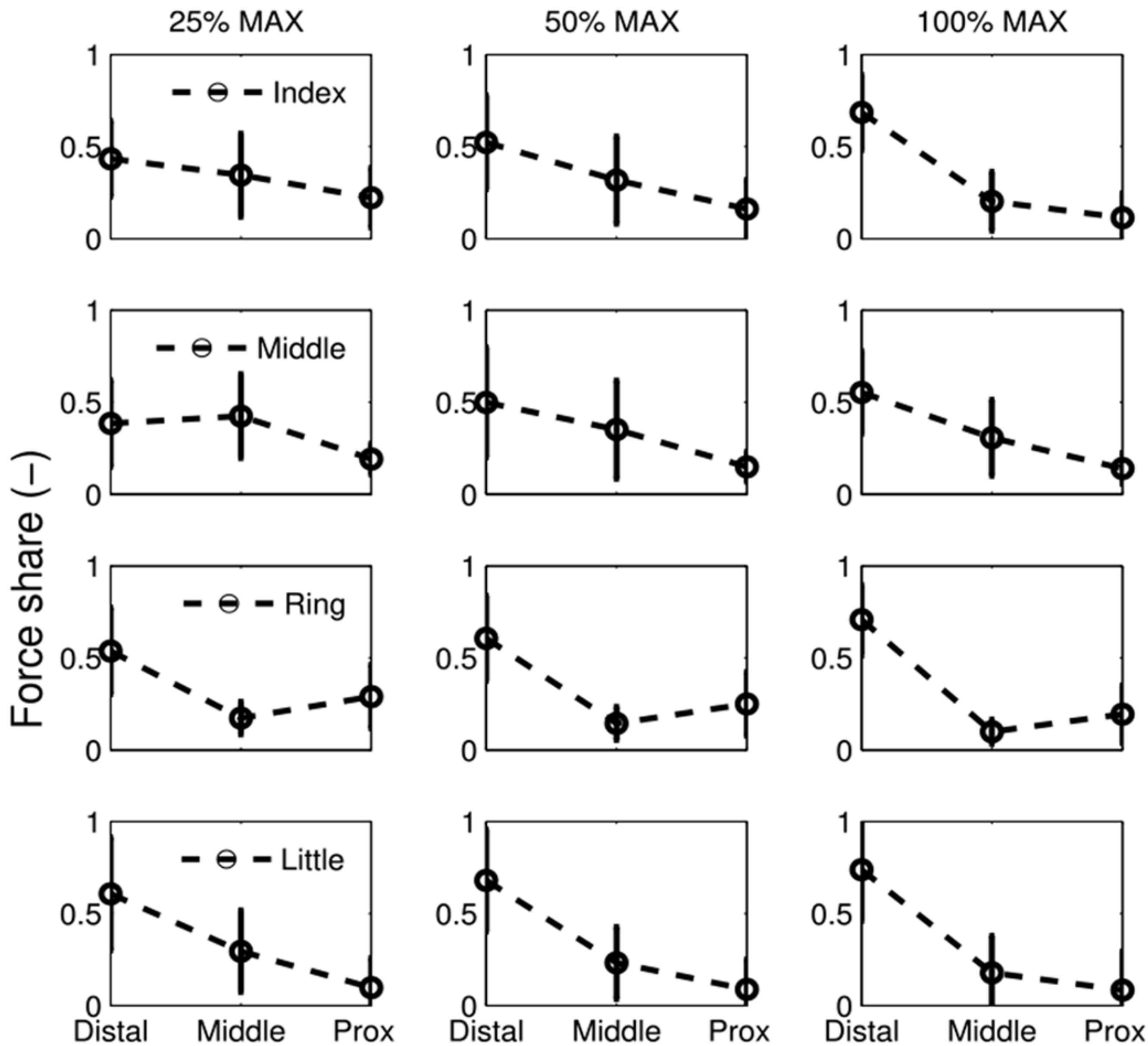


Fig. 2.
Force share among the distal, middle, and proximal finger segments when gripping on a tennis ball. The first. second, and third column of the plots are for the grip force levels of 25%. 50%. and 100% MAX. respectively; whereas the first. second, third, and fourth row of the plots represent the force distributions in the little, ring, middle, and index finger, respectively.

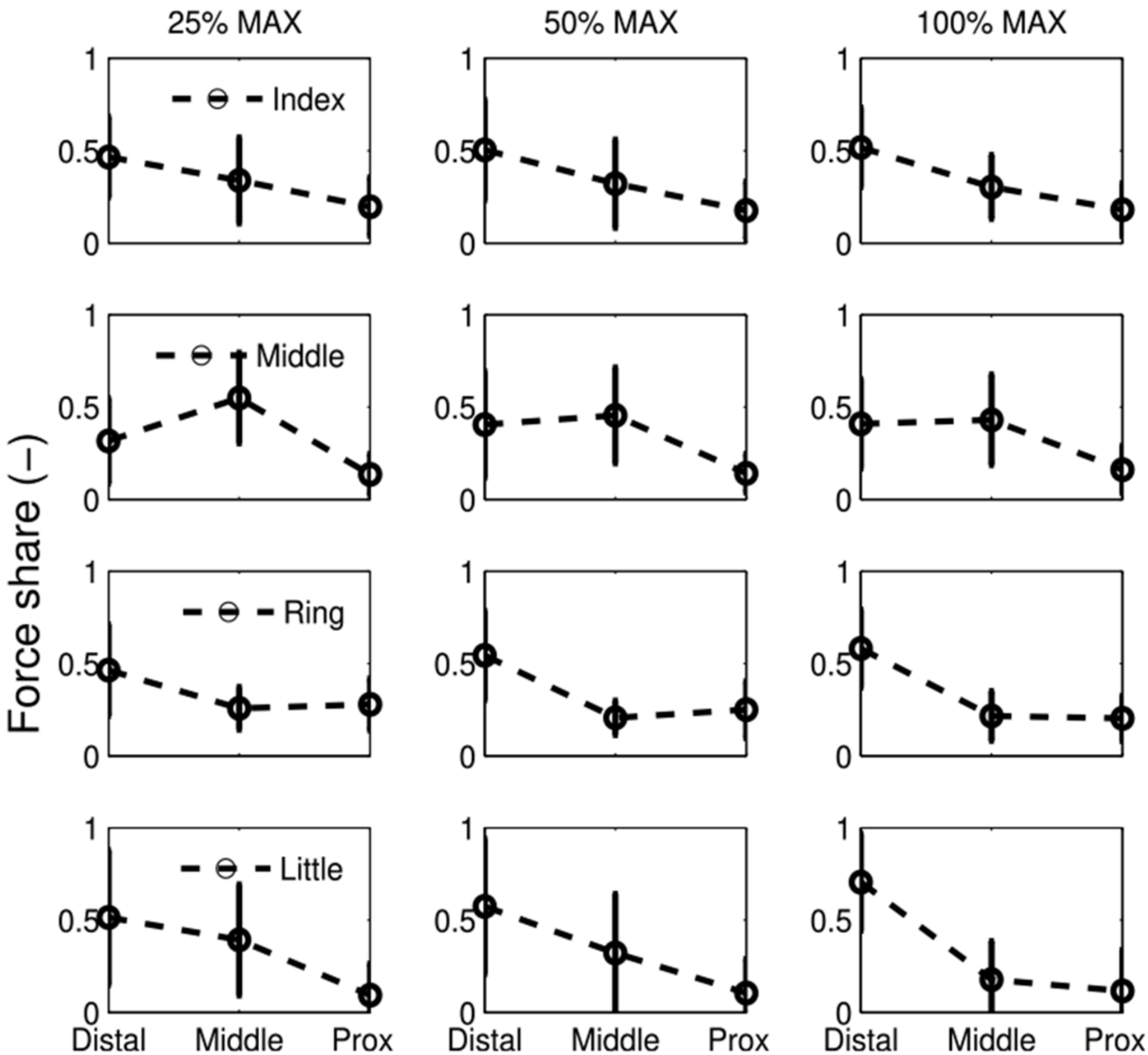


Fig. 3.

Force share among the distal, middle, and proximal finger segments when gripping on a rehabilitation squeeze ball. The first. second, and third column of the plots are for the grip force levels of 25%. 50%. and 100% MAX. respectively; whereas the first. second, third, and fourth row of the plots represent the force distributions in the little, ring, middle, and index finger, respectively.

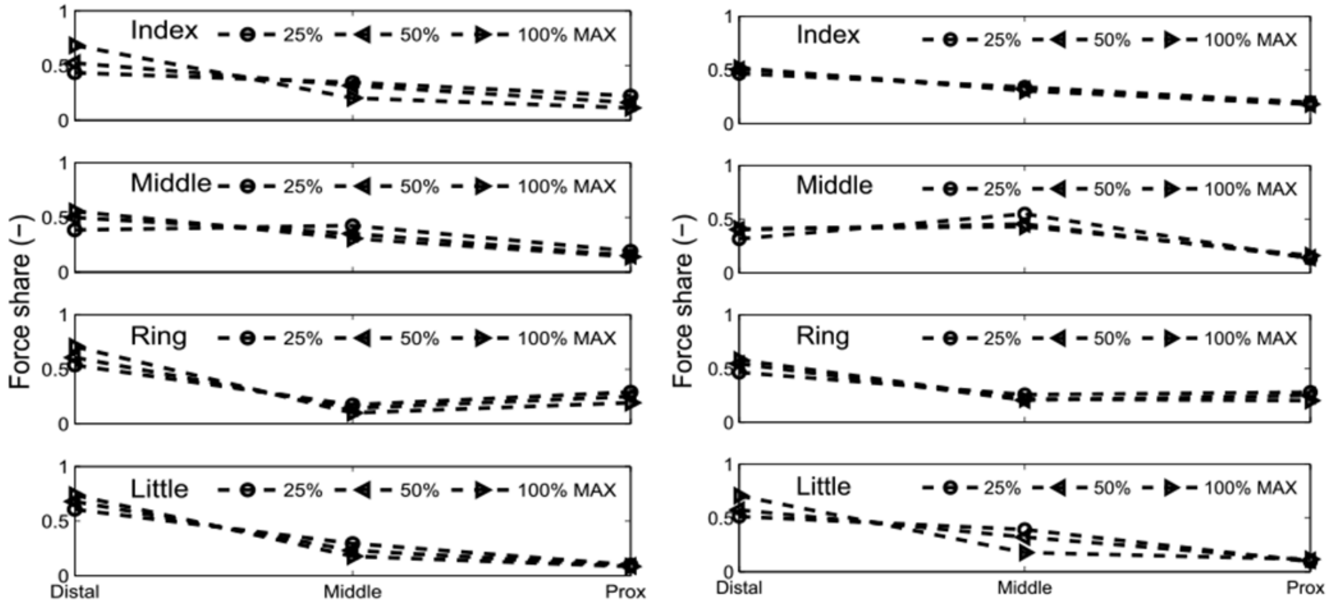


Fig. 4.

The force share among fingers for three different grip force levels. Left: tennis ball grip. Right: rehabilitation squeeze ball grip.

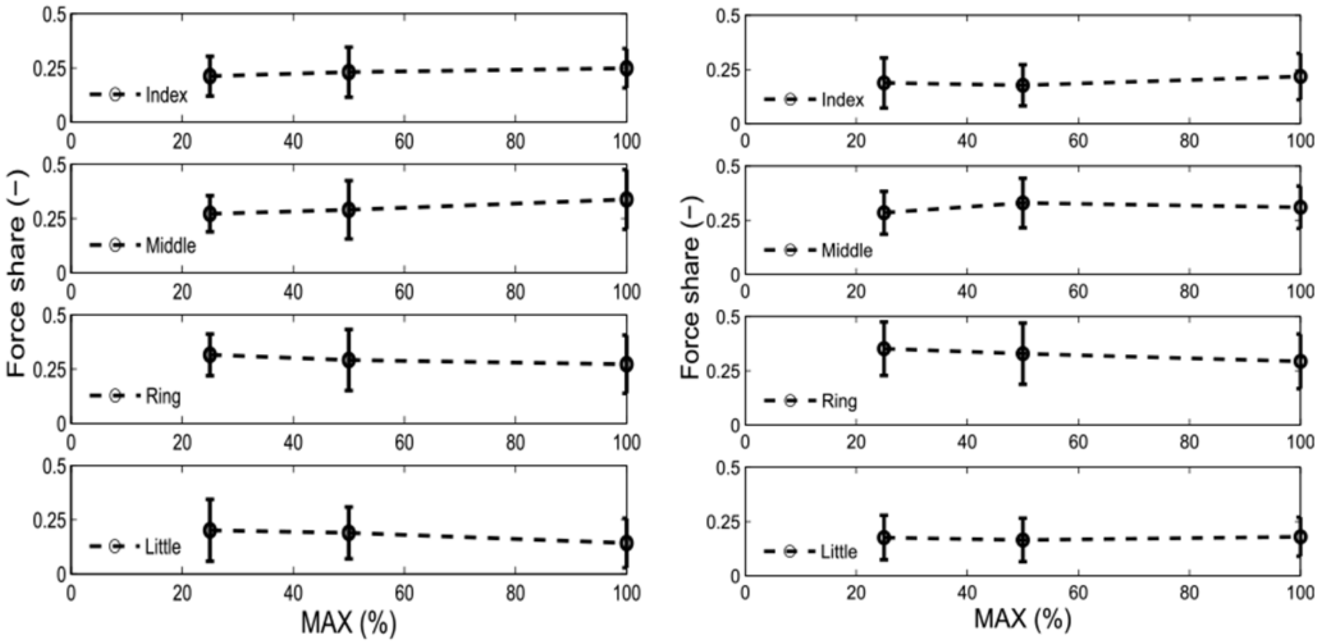
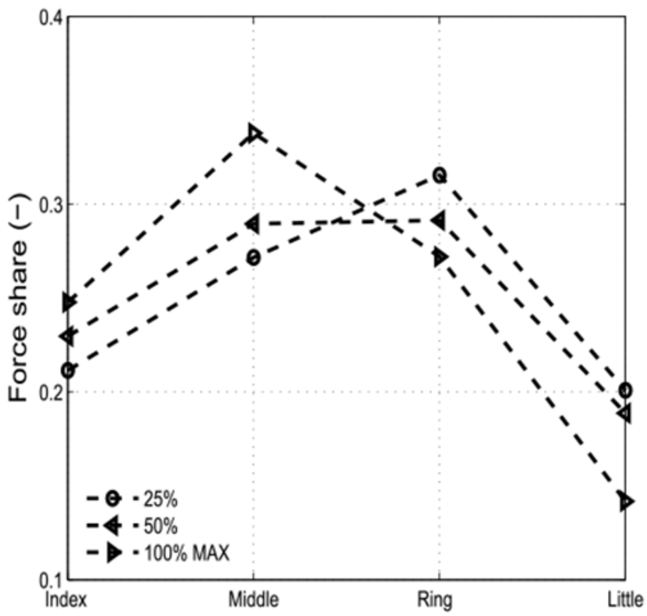


Fig. 5.

The grip forces shared by each finger as a function of the grip force level. Left: tennis ball grip. Right: rehabilitation squeeze ball grip.



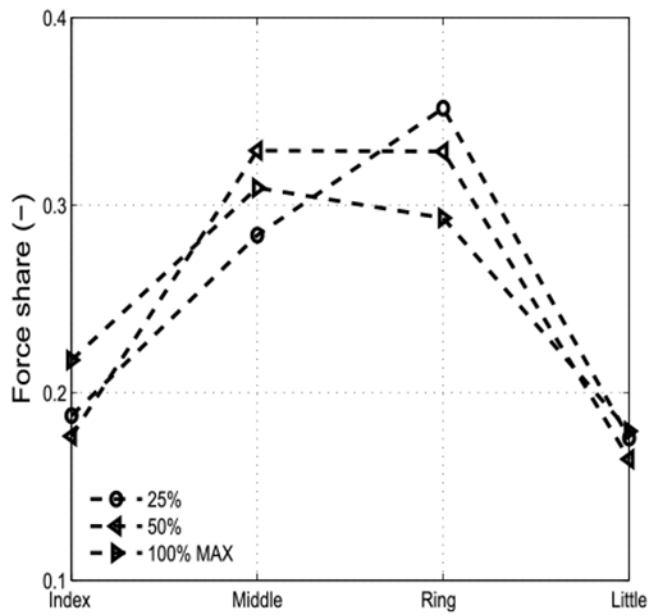


Fig. 6.
The effect of the grip force level on the force sharing on each individual finger. Left: tennis ball grip. Right: rehabilitation squeeze ball grip.

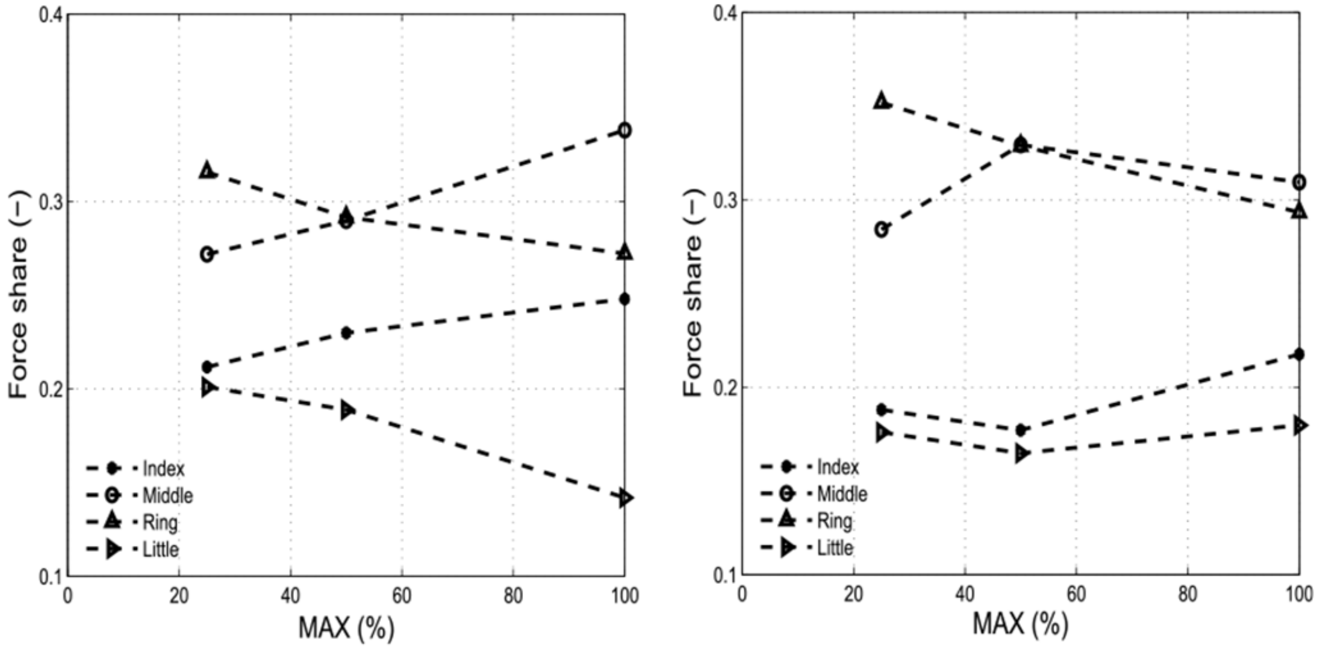


Fig. 7.
The force sharing on each individual finger as a function of grip force level. Left: tennis ball grip. Right: rehabilitation squeeze ball grip.

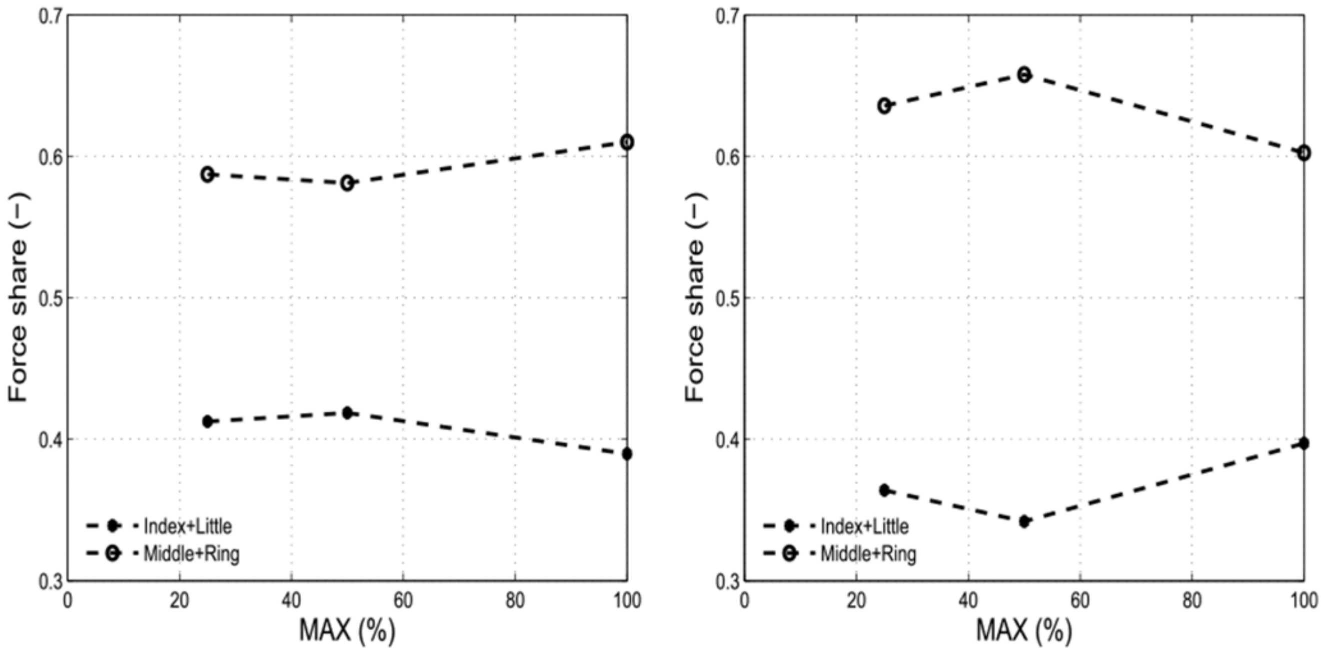


Fig. 8.

Comparison of the force share on the index and ring fingers and that on the index and little fingers. Left: tennis ball grip. Right: rehabilitation squeeze ball grip.