JESK
J Ergon Soc Korea 2016; 35(5): 413-423
http://dx.doi.org/10.5143/JESK.2016.35.5.413
http://jesk.or.kr eISSN:2093-8462

Effect of Task Direction on the Maximal Pushing, Pulling, Twisting, and Grip Forces

Jangwhon Yoon

Department of Physical Therapy, Hoseo University, Chungcheongnam-do, 31499

Corresponding Author
Jangwhon Yoon
Department of Physical Therapy, Hoseo University, Chungcheongnam-do, 31499
Mobile : +82-10-3400-7666
Email : jyoon@hoseo.edu

Received : August 25, 2016
Revised : September 20, 2016
Accepted : October 03, 2016

Objective: The aims of this study are to understand the effects of task (pushing, pulling, and clockwise and counter clockwise twisting) direction on the maximal output and their grip forces and to explore the relationship between the maximal output and the grip forces.

Background: Knowing the normative maximal grip force is not enough to design a good hand tool. The industrial designers should understand the required grip forces in various motions toward a specific direction to make an effective and efficient hand tool.

Method: Eighteen healthy volunteers participated in the series of isometric maximal output force tests. A custom-made force measuring equipment collected the output and the grip forces for three seconds. Force measurements along the vertical, coronal and sagittal axes were randomly repeated three times.

Results: The pulling was strongest and the pushing was weakest in all directions. The effect of motion on the output forces varied in different directions. The corresponding grip force increased in the order of pushing, pulling, clockwise twisting, and counter clockwise twisting in all directions. The maximal output and their grip forces were highly correlated but the relationship was affected by motion and direction. The regression coefficient was greatest in pulling and smallest in clockwise twisting.

Conclusion: The effect of motion on the output forces varied in different directions. The maximal output and their grip forces were correlated but the relationship was affected by motion and direction.

Application: Findings of this study can be valuable information for industrial designers to develop more productive hand tools and work stations to help preventing the musculoskeletal disorders at work.

Keywords: Handle design, Grip force, Pushing, Pulling, Twisting

1. Introduction

When designing a handle tool, an industrial designer needs to consider how much force is required for a pursuing task. The required force is function of the grip strength and the friction between hand and handle (Seo et al., 2010). When the grip force is too greater than required for the task, the excessive effort can lead to fatigue (Bystrom and Fransson-Hall, 1994; Rohmert, 1973), furthermore, to the cumulative trauma disorders in the hands and forearms (Bystrom and Kilbom, 1990; National Research Council and Institute of Medicine, 2001).

Normative maximal grip forces (Balogun et al., 1991; Gunther et al., 2008; Lin et al., 2013; Mathiowetz et al., 1985) are available for age and gender. Several factors influence the maximal grip force: age (Angst et al., 2010; Kong et al., 2009), gender (Dempsey and Ayoub, 1996; Morse et al., 2006), grip type (Dempsey and Ayoub, 1996; Kong et al., 2009), grip width (Dempsey and Ayoub, 1996; Jung et al., 2007; Kong et al., 2013; Lee et al., 2009; Shivers et al., 2002), muscle and tendon compliance (Loren et al., 1996), joint position (Berme et al., 1977), neurological problems (Boissy et al., 1999), and relevant body configurations (Balogun et al., 1991). However, just knowing the normative maximal grip force is not enough to develop a good hand tool. For an orange squeezer as an example, two forces are needed: the squeezing force to compress the orange and the grip force to avoid slippage. Squeezing can be done by pushing, pulling, or twisting toward different directions. The squeezing and its corresponding grip force can be affected by the motion and the direction. There should be a better motion and an easier direction to squeeze the orange. The industrial designers should understand the relationship between the required grip forces in different motion which is affected by the direction of motion to make an effective and efficient hand tool.

The aims of this study were to investigate: 1) the effect of motion (pushing, pulling, and twisting) and direction on the output force; 2) the effect of motion and direction on the corresponding grip forces while exerting maximal output forces; and 3) the relationship between the output and grip forces by motion and direction. The findings of this study may be useful to improve the effectiveness and accessibility of hand and to prevent the musculoskeletal disorders in the upper extremities.

2. Method

2.1 Participants

Eighteen (10 females and 8 males) healthy young (35.8 ± 9.0 year old) volunteers without any pain during the past month or history of neuromuscular disorders in the spine and upper extremities participated. Height was 170.9 ± 10.4cm and weight was 71.1 ± 15.4Kg. All participants were asked to read and sign and consent form approved by the Office of Institutional Board of Research Associates of New York University School of Medicine.

2.2 Study design

The two independent variables in this experiment were task direction and motion type and the two dependent variables were the output and grip forces. The task directions were forward, upward and toward the non-dominant (left for right-handed participants) side. The motion was pushing, pulling, clockwise twisting and counter-clockwise twisting. The grip, pushing and pulling forces were measured in Newton (N) and the twisting forces were in Newton-centimeter (Ncm). All participants completed a total of 36 trials (4 motions in 3 directions for 3 repetitions). Only the dominant hand was tested because the hand tools are mostly used with it. Dominant hand was the hand with which they could throw a ball further. There were only 2 males and 1 female who were left handed in this study.

2.3 Instrumentation

An expert industrial designer at the SmartDesign (New York, NY) participated in the designing and producing the equipment used in this study to measure the grip and output forces (Figure 1). Force sensors (FlexiForce, Tekscan, Inc. Boston, MA) inside the handle measured the grip force of individual fingers and the over grip force was calculated by adding them together. The bottom half of the equipment allows very small amount (less than 2mm) of pushing, pulling and twisting to both directions. Pushing and pulling force were measured with the middle two sensors in Figure 1. Twisting torque was calculated by multiplying the force measured with the bottom two sensors in Figure 2 B and the distance (moment arm) between the axis of rotation and the center of the sensors. The force signal was collected at 100Hz using a data acquisition board (National Instruments, Austin, TX). LabVIEW (version 6, National Instruments, Austin, TX) software was used for data processing. The collected electrical signals from the force sensors were converted in N and Ncm after calibration.

Figure 1. A custom-made equipment used for output (pushing, pulling, and twisting) and grip force measurement

2.4 Procedure

The force measuring equipment was fixed on a height adjustable table and the table was adjusted to keep the participant's elbow flexion at 90° in sitting. All participants were instructed to gradually exert their maximal output force for three seconds after a few familiarizing trials. Pushing, pulling, clockwise twisting and counter-clockwise twisting tasks were performed forward, upward and toward the left side (right for left hand dominant participants) in sitting. All the taks were isometrically performed and repeated three times in a random order. Upward tasks were performed with the elbow in contact with the side of trunk and the wrist in neutral position. Forward tasks were performed with no shoulder flexion, the elbow in contact with the side of trunk, and the wrist in slight ulnar deviation. Sideway tasks were performed with no shoulder abduction, the elbow in 90° flexion, the forearm in pronation and the wrist in neutral position. Participants were asked to maintain their maximal output force until asked to stop (three seconds after reaching their maximal exertion). A middle one second window of the stable maximal force was visually selected and averaged for analysis.

2.5 Statistical analysis

Repeated measures ANOVA (analysis of variance) was used to test the main and interaction effects of task direction and motion type on the output and grip forces. When there was a significant interaction effect, the motion types were separately tested and *post-hoc* analysis compared the pairwise differences using the Bonferroni correction. Pearson correlation coefficient was used for the relationship between the grip and output forces. SPSS (version 18) was used for all statistical analysis.

3. Results

3.1 Output force

There was a significant interaction between motion and direction ($p = 0.01$) which means the output force pattern affected by

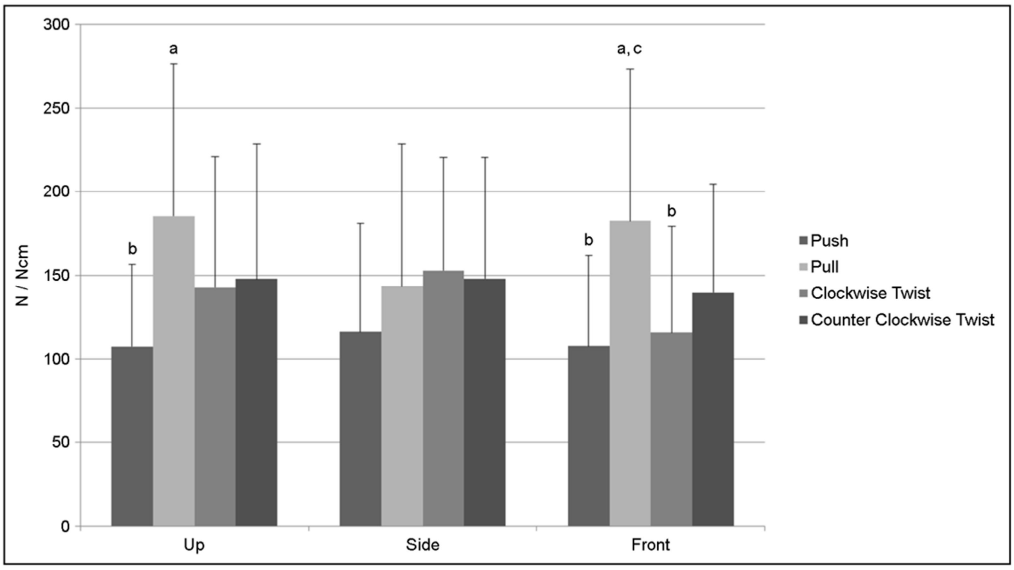

Figure 2. Output forces to up, side and forward directions (a: significantly ($p < 0.05$) different from pushing force; b: significantly different from pulling force; c: significantly different from clockwise twisting torque; T bars indicate the standard deviations)

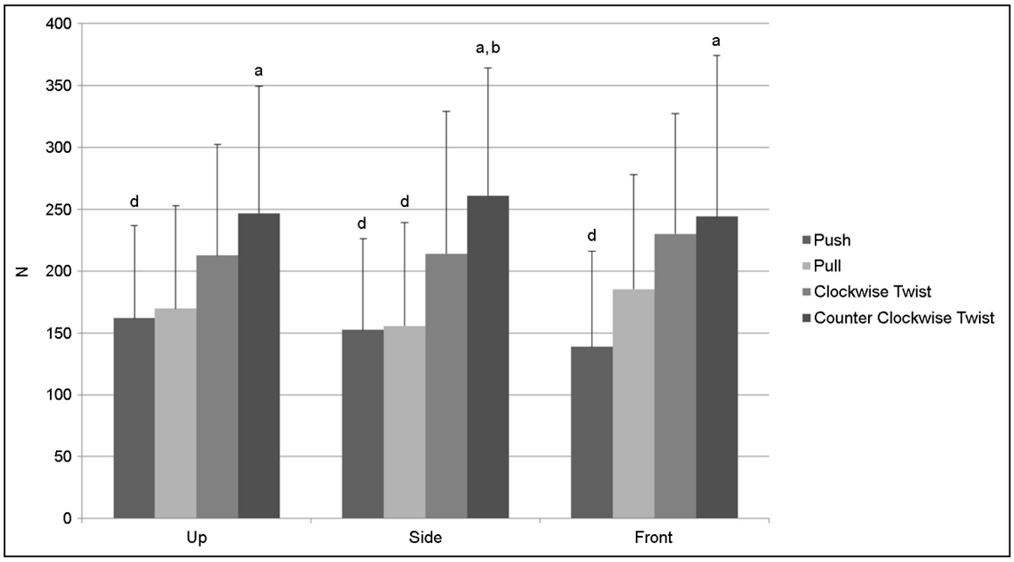

Figure 3. Grip forces while exerting maximal output forces to up, side and forward directions (a: significantly ($p < 0.05$) different from pushing force; b: significantly different from pulling force; d: significantly different from counter clockwise twisting torque; T bar indicates the standard deviation)

motion type was not same in different direction. In the separated analysis by direction, the effect of motion on the output force was greatest (F=12.97, p<0.01) in upward direction, less (F=8.74, p<0.01) in forward direction, and smallest (F=1.04, p=0.37) toward non-dominant side direction. Pulling was stronger than pushing in upward and forward directions. Pair-wise comparisons are displayed in Figure 2.

3.2 Grip force

There was no significant interaction between direction and motion (p=0.27) on the grip force while exerting output force. In all directions, grip force was strongest while counter clockwise twisting and weakest while pushing. Effect of motion was all significant in forward (F=9.97, p<0.01), side (F=10.24, p<0.01), and upward (F=10.66, p<0.01) directions. Pair-wise comparisons are displayed in the Figure 3.

3.3 Relationship between output and grip forces

The maximal output and their grip forces were highly (r=0.64) correlated (Figure 4). When separated by direction and motion (Figure 5), the relationship was strengthened especially with the counter clockwise twisting and toward the side direction. The strongest correlation (r=0.86) was observed while exerting the counter clockwise twisting in forward direction but the slope of correlation (β=0.43) was not the greatest. The steepest slop of correlation (β=0.80) between grip and output forces was seen in pulling sideway.

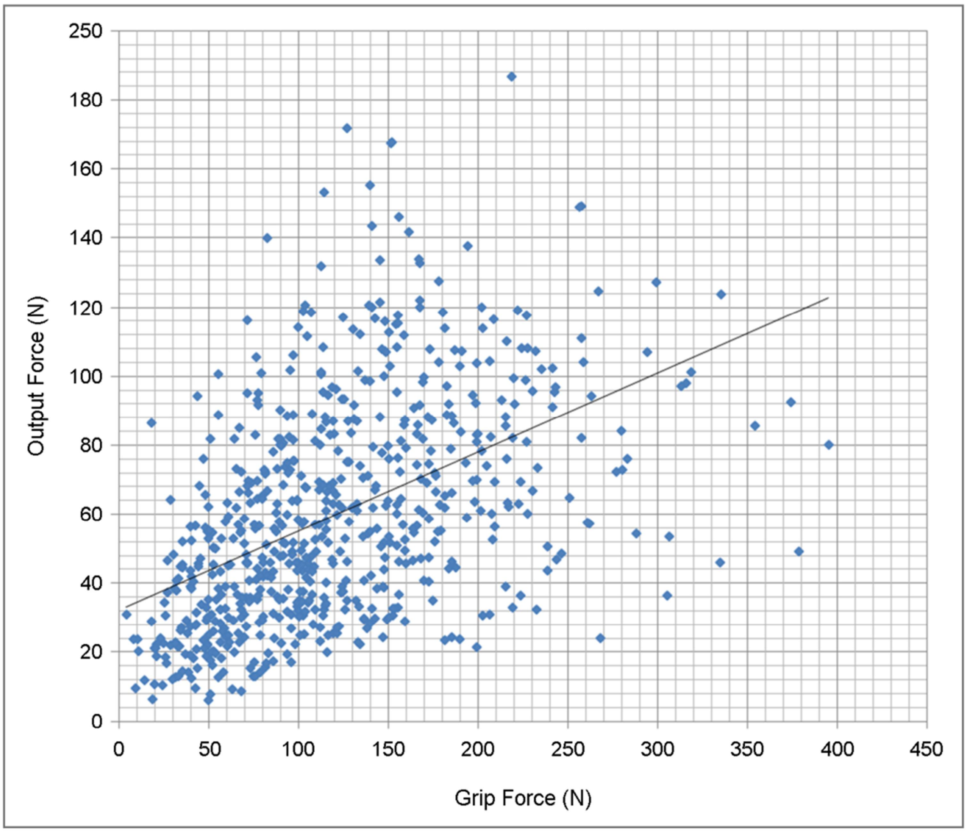

Figure 4. Correlation between output force and grip force (all 648 data). r^2 = 0.41

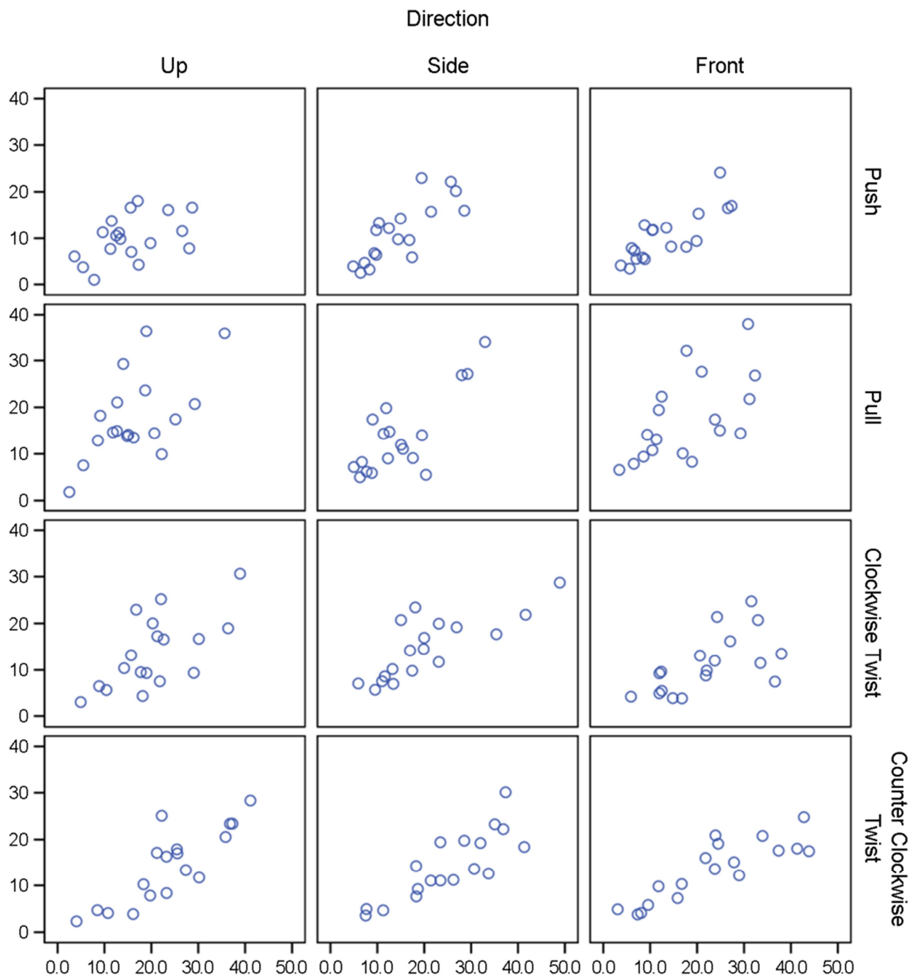

Figure 5. Scatter plots of grip (horizontal axis) and output (vertical axis) forces by motion and direction

4. Discussion and Conclusion

4.1 Output force

The interaction effect between motion and task direction on the output forces was significant. The pulling and clockwise twisting forces were more affected by the task direction than the pushing and counter clockwise twisting. Pulling sideway (toward left for the right handed) was about 25% weaker than pulling downward and backward. The possible reasons are 1) the muscles in the trunk are limited in producing isometric horizontal rotation when pulling sideway (Lin et al., 2013); and 2) major side pulling muscles in this study are shoulder external rotators which are much smaller than shoulder and elbow extensors participating in downward and backward pulling. Similar tendency was observed in the larger anthropometric database (SizeKorea, 2012). Forward clockwise twisting was weaker than upward and sideway clockwise twisting because forward clockwise twisting was performed with the wrist in ulnar deviation and this position of wrist limits the wrist flexion force.

Comparing pushing or pulling force to twisting force is not quite meaningful because it is not very practical substituting a hand tool design with twisting motion with a pushing or pulling design or vice versa. However, comparing pushing and pulling forces is practical and meaningful. Fingdings of this study can be helpful in makin a work place more productive and efficient. Pulling backward and downward was stronger than pushing forward (69%) upward (73%) directions (Figure 2). Sideway pulling and pushing were not significantly different. Backward pulling was 60% stronger than forward pushing in sitting and upward pushing was 7% weaker than downward pulling in standing in the database (SizeKorea, 2012). For a tool like a saw, it is worthy to consider that pulling produces more force than pushing especially along the sagittal and vertical axes. The American saw cuts the wood with pushing motion while the Asian saw does with pulling motion. The Asian saw can be more efficient especially in upward and forward directions.

In general, people does not usually have a problem in opening (counter clockwise twisting) a jar when those were fastened (clockwise twisting) by same person. Counter clockwise twisting was 20% stronger (but not statically significant) than clockwise twisting only in forward direction in this study. There was 7% difference in standing position in the large database (SizeKorea, 2012). The torques between the two twisting tasks in the upward and sideway directions were only 2~3% different in this study. Previous studies (Morse et al., 2006; Seo et al., 2007) reported 20% greater clockwise twisting in upward direction. These discrepancies can be from the different body position, handle size, and friction of the handle among studies.

Pushing up was weaker because its direction of exertion was against gravity and the tension of biceps muscles is less than that of triceps muscles (Kisner and Colby, 2012). Pulling forces along the vertical and frontal axes were stronger than pushing force while sideway pulling and pushing were found not so different. Twisting torques toward each direction were not significantly different in this study. Previous studies (Morse et al., 2006; Seo et al., 2007) reported 20% greater force with twisting with more flexed wrist position. 7% difference was observed in an anthropometric database (SizeKorea, 2012). In a previous study of twisting a circular object similar to door nap, clockwise torque with forearm supination was greater than counter-clockwise torque (Shim et al., 2007).

4.2 Grip force

Grip forces while exerting the maximal output (pushing, pulling, or twisting) force are less than maximal grip force. The observed grip forces in this study (250N for male and 135N for female) are far less than maximal voluntary grip strength. The previously reported maximal grip force is above 350N for male and 200N for female (Balogun et al., 1991; Gunther et al., 2008; Mathiowetz et al., 1985; SizeKorea, 2012). When more than one muscle groups are activated simultaneously in a multi-task like in this study (i.e., pulling and gripping), each muscle group's force does not reach to the maximal force of single muscle group during their own exertion. In the study by Seo (Seo, 2009), the grip force during maximal push exertion was only 74% of participants' maximum grip force. Similar phenomena were seen in individual fingers during multiple finger prehension (Kionshita et al., 1995), and in bilateral leg exertion (Vandervoort et al., 1984). It was thought to be a mutual afferent inhibition of the cerebral cortex (Ohtsuki, 1981), or an unexceedable limitation in central neural drive (Li et al., 1998; Li et al., 1998). In this study, the participants were asked to exert their maximal pushing, pulling, and twisting forces not their maximal output and grip forces. Therefore, they focused on the output forces to be their maximum and they did not concern about their grip forces. The grip force were implicitly controlled enough to avoid slippage.

The grip force during the maximal output force exertion was affected by type of motion, but not by task direction or the interaction between the motion and direction. Grip force during counter clockwise twisting was strongest in all directions (Figure 3). The counter clockwise twisting in this study was performed mainly with the wrist extension. Wrist extension stretches the wrist and finger flexor muscles and this stretching can contribute to the higher grip force by the length-tension relationship of skeletal muscles (Kisner and Colby, 2012). To avoid slipping accident while using a hand tool, pushing task is better to be substituted with pulling because the grip force during pushing was always weakest in all directions.

4.3 Relationship between output and grip forces

The higher grip force is required for the greater output force in a single task. Similar output forces with different motions in different directions do not require same level of grip force. The contribution of grip force on the output force varies by direction and motion in this study. The contribution slope of grip force on the output force was twice steeper in pulling downward than in pushing upward (Figure 5). It means that a task performed with pulling requires less grip force for an identical output force. In other words, pulling is more efficient in converting the grip force to the output force than pulling. Counter clockwise twisting was somewhat more efficient than clockwise twisting. It suggests that a well-designed hand tool can improve the productivity with less effort.

4.4 Considerations in design

A handle for luggage must be approached differently than a bicycle handle. Human factors and ergonomics made a great progression in design of the handle. Good handle should be comfortable to grip, safe to avoid slippage, effective to be productive and efficient to save the unnecessary effort (Patkin, 2001). Industrial designer must review the related tangibles, such as environment, duration, usage and etc. and prioritize the features of a handle in designing. Understanding the relationship between the output and grip forces provides valuable information for industrial designers to create a better hand tool. For instance, a grip of orange squeezer needs to be comfortable, safe, effective and efficient. This study found that 1) pulling is stronger than pushing, 2) pulling downward was strongest among the pulling forces in different directions, and 3) it required the least grip force. As an example, an orange squeezer can be more effective in producing squeezing force and efficient by requiring the minimal grip force, compared to other motions toward other directions.

Limitation of this study was, firstly, the samples size was not large enough to show the statistical significance in some output and grip forces or to present a normative value, however, the relationship between grip and output force was observable. Secondly, the participants were not professionals who might be more skillful and efficient in exerting maximal output force. Thirdly, the measuring equipment did not look like any hand tool that is used for actual activities of daily living. Fourthly, the age range of participants was somewhat wide which can weaken the power of statistical analysis. There are needs for further studies comparing different handle design to exert same level of output force and testing the effect of glove or slippery hand on the relationship between grip and output forces. Furthermore, the relationship between output and grip force during submaximal exertion also needs to be studied because submaximal force is more frequently used in the real work places.

The aims of this study were to understand the effects of motion and direction on the output forces and the relationship between the maximal output and the corresponding grip forces in different directions. The effect of motion on the output forces varied in different directions. The maximal output and their grip forces were correlated but the relationship was affected by motion and direction. Findings of this study could be informative for industrial designers to develop more productive hand tools and to prevent the musculoskeletal disorders in the upper extremities.

Acknowledgements

This project was partially funded by the pilot projects of the NIOSH Educational and Research Center (ERC) of New York and New Jersey, grant # T42-OH008422.

References

Angst, F., Drerup, S., Werle, S., Herren, D.B., Simmen, B.R. and Goldhahn, J., Prediction of grip and key pinch strength in 978 healthy subjects. *BMC Musculoskelet Disord*, 11, 94, 2010. doi:10.1186/1471-2474-11-94

Balogun, J.A., Adenlola, S.A. and Akinloye, A.A., Grip strength normative data for the harpenden dynamometer. *The Journal of Orthopaedic and Sports Physical Therapy*, 14(4), 155-160, 1991.

Berme, N., Paul, J.P. and Purves, W.K., A biomechanical analysis of the metacarpophalangeal joint. *Journal of Biomechanics*, 10(7), 409-412, 1977.

Boissy, P., Bourbonnais, D., Carlotti, M.M., Gravel, D. and Arsenault, B.A., Maximal grip force in chronic stroke subjects and its relationship to global upper extremity function. *Clinical Rehabilitation*, 13(4), 354-362, 1999.

Bystrom, S.E. and Fransson-Hall, C., Acceptability of intermittent handgrip contractions based on physiological response. *Human Factors*, 36(1), 158-171, 1994.

Bystrom, S.E. and Kilbom, A., Physiological response in the forearm during and after isometric intermittent handgrip. *European Journal of Applied Physiology and Occupational Physiology*, 60(6), 457-466, 1990.

Dempsey, P.G. and Ayoub, M.M., The influence of gender, grasp type, pinch width and wrist position on sustained pinch strength. *Interantional Journal of Industrial Ergonomics*, 17, 259-273, 1996.

Gunther, C.M., Burger, A., Rickert, M. and Schulz, C.U., Key pinch in healthy adults: normative values. *J Hand Surg Eur*, Vol, 33(2), 144-148, 2008. doi:10.1177/1753193408087031

Jung, M.-C., Kim, D.-M. and Kong, Y.-K., Evaluation of individual finger force to grip strength in various grip spans and hand sizes. *Journal of the Ergonomics Society of Korea*, 26(3), 59-65, 2007.

Kinoshita, H., Kawai, S. and Ikuta, K., Contributions and co-ordination of individual fingers in multiple finger prehension. *Ergonomics*, 38(6), 1212-1230, 1995. doi:10.1080/00140139508925183

Kisner, C. and Colby, L.A., (2012). Chapter 3. Range of Motion *Therapeutic Exercise* (2012). Philadelphia, PA: F. A. Davis.

Kong, Y.-K., Park, H., Kim, D., Lee, T., Roh, E., Lee, S. and Kang, H.-S., A Study on the Difference of Total Grip Strength and Individual Finger Force between Dominant and Non-dominant Hands in Various Grip Spans of Pliers. *Journal of the Ergonomics Society of Korea*, 32(6), 503-509, 2013.

Kong, Y.-K., Sohn, S.-T., Kim, D.-M. and Jung, M.-C., Grip force, finger force, and comfort analyses of young and old people by hand tool handle shapes. *Journal of the Ergonomics Society of Korea*, 28(2), 27-34, 2009.

Lee, S.J., Kong, Y.K., Lowe, B.D. and Song, S., Handle grip span for optimising finger-specific force capability as a function of hand size. *Ergonomics*, 52(5), 601-608, 2009. doi:10.1080/00140130802422481

Li, Z.M., Latash, M.L., Newell, K.M. and Zatsiorsky, V.M., Motor redundancy during maximal voluntary contraction in four-finger tasks. *Experimental Brain Research.Experimentelle Hirnforschung.Experimentation Cerebrale*, 122(1), 71-78, 1998.

Li, Z.M., Latash, M.L. and Zatsiorsky, V.M., Force sharing among fingers as a model of the redundancy problem. *Experimental Brain Research.Experimentelle Hirnforschung.Experimentation Cerebrale*, 119(3), 276-286, 1998.

Lin, J.H., McGorry, R.W. and Maynard, W., One-handed standing pull strength in different postures: normative data. *Appl Ergon*, 44(4), 603-608, 2013. doi:10.1016/j.apergo.2012.12.001

Loren, G.J., Shoemaker, S.D., Burkholder, T.J., Jacobson, M.D., Friden, J. and Lieber, R.L., Human wrist motors: biomechanical design and application to tendon transfers. *J Biomech*, 29(3), 331-342, 1996.

Mathiowetz, V., Kashman, N., Volland, G., Weber, K., Dowe, M. and Rogers, S., Grip and pinch strength: normative data for adults. *Archives of Physical Medicine and Rehabilitation*, 66(2), 69-74, 1985.

Morse, J.L., Jung, M.C., Bashford, G.R. and Hallbeck, M.S., Maximal dynamic grip force and wrist torque: the effects of gender, exertion direction, angular velocity, and wrist angle. *Appl Ergon*, 37(6), 737-742, 2006. doi:10.1016/j.apergo.2005.11.008

National Research Council, and Institute of Medicine. *Musculoskeletal disorders and the workplace: Low back and upper extremities*. Washington, DC: National Academy Press. 2001.

Ohtsuki, T., Decrease in grip strength induced by simultaneous bilateral exertion with reference to finger strength. *Ergonomics*, 24(1), 37-48, 1981. doi:10.1080/00140138108924828

Patkin, M., (2001). A check-list for handle design. Web Page. http://ergonomics.uq.edu.au/eaol/handle.pdf

Rohmert, W., Problems in determining rest allowances Part 1: use of modern methods to evaluate stress and strain in static muscular work. *Applied Ergonomics*, 4(2), 91-95, 1973.

Seo, N.J., Dependence of safety margins in grip force on isometric push force levels in lateral pinch. *Ergonomics*, 52(7), 840-847, 2009. doi:10.1080/00140130802578555

Seo, N.J., Armstrong, T.J., Ashton-Miller, J.A. and Chaffin, D.B., The effect of torque direction and cylindrical handle diameter on the coupling between the hand and a cylindrical handle. *J Biomech*, 40(14), 3236-3243, 2007. doi:10.1016/j.jbiomech.2007.04.023

Seo, N.J., Armstrong, T.J. and Young, J.G., Effects of handle orientation, gloves, handle friction and elbow posture on maximum horizontal pull and push forces. *Ergonomics*, 53(1), 92-101, 2010. doi:10.1080/00140130903389035

Shim, J.K., Huang, J., Hooke, A.W., Latsh, M.L. and Zatsiorsky, V.M., Multi-digit maximum voluntary torque production on a circular object. *Ergonomics*, 50(5), 660-675, 2007. doi:10.1080/00140130601164516

Shivers, C.L., Mirka, G.A. and Kaber, D.B., Effect of grip span on lateral pinch grip strength. *Hum Factors*, 44(4), 569-577, 2002.

SizeKorea. (2012). Muscle strength database. http://sizekorea.kats.go.kr/ http://sizekorea.kats.go.kr/

Vandervoort, A.A., Sale, D.G. and Moroz, J., Comparison of motor unit activation during unilateral and bilateral leg extension. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 56(1), 46-51, 1984.

Author listings

Jangwhon Yoon: jyoon@hoseo.edu
Highest degree: PhD in Ergonomics and Biomechanics at New York University
Position title: Assistant Professor, Dept. of Physical Therapy at Hoseo University
Areas of interest: Work-related musculoskeletal disorder; Manual material handling; Ergonomic Product Design