INTERNATIONAL JOURNAL OF OCCUPATIONAL SAFETY AND ERGONOMICS (JOSE)
https://doi.org/10.1080/10803548.2021.1950992

The effects of pistol grip power tools on median nerve pressure and tendon strains

Ryan Bakker[a], Mayank Kalra[a], Sebastian S. Tomescu[b], Robert Bahensky[a] and Naveen Chandrashekar[a]

[a]Mechanical and Mechatronics Engineering, University of Waterloo, Canada; [b]Sunnybrook Health Sciences Centre, University of Toronto, Canada

ABSTRACT

Objectives. Tendonitis and carpal tunnel syndrome are common cumulative trauma disorders that can occur with repetitive usage of pistol grip power tools. The role of reaction torque resulting in a forceful rotary displacement of the tool handle, as well as the role of applied grip force, is not clear in the development of these disorders. This study aimed to quantify the flexor tendon strains and median nerve pressure during a typical power tool operation securing a threaded fastener. *Methods.* Six fresh-frozen cadaver arms were made to grip a replica pistol grip power tool using static weights to apply muscle forces. A 5-Nm torque was applied to the replica power tool. The median nerve pressure and strains in the flexor digitorum profundus and superficialis tendons were measured using a catheter and strain gauges, at three wrist flexion angles. *Results.* The peak tendon strains were between 1.5 and 2% and were predominantly due to the grip force more than the transmitted torque. Median nerve pressure significantly increased with the wrist flexed versus extended. *Conclusion.* The results indicate that the contribution of the grip force to the tendon strain and median nerve pressure was greater than the contribution from the reaction torque.

KEYWORDS
tendonitis; cumulative trauma disorder; power tools; carpal tunnel syndrome; grip force; median nerve pressure

1. Introduction

Wrist-related cumulative trauma disorders, such as carpal tunnel syndrome (CTS) and tendonitis, are common work-related injuries that develop chronically over time [1–3]. The use of hand-held pistol grip power tools in industries such as manufacturing, agriculture and mining are commonly associated with both CTS and tendonitis [3–7]. Exposure to the large repetitive forces exerted by the user to support the tool, engage the bit and resist the torque reaction forces stress the body and contribute to tendonitis and CTS [7–9].

CTS is caused by excessive pressure on the median nerve [10], which runs through the carpal tunnel. During pistol grip power tool operation, changes to the median nerve pressure (MNP) can be caused by gripping the handle [2,11–13] and deviating from a neutral wrist position [13–15]. Tendonitis is inflammation of a tendon caused by cumulative trauma through repetitive strain [16]. The tendons of the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS) muscle groups travel through the carpal tunnel and are responsible for applying grip force and engaging the tool trigger during power tool operation. These tendons are commonly associated with tendonitis [17,18]. While muscular contractions cause these tendons to experience strain during hand-tool gripping tasks, the tendons may experience additional strain from a forceful tool handle rotary displacement due to a reaction torque at the end of a fastener's travel.

There are significant bodies of research on CTS [13,14,19,20] and tendonitis or tendon forces [16,21–23]. Cadaveric wrist and hand simulators have been used for many of these investigations. Simulated muscle forces were applied by suspending weights from the tendons, which either manipulates the kinematics [21] or applies grip [14,23] to the hand. Investigators of CTS have measured changes to the carpal tunnel pressure (MNP) by using hypodermic needles [10,24,25], transducer catheters [14,20,26] or bulb transducers [14,27]. While these studies investigated causal links between power tool operation and the incidence of CTS and tendonitis, they applied lower tendon loads than what is suspected during power grip [17,28].

None of these studies directly measured wrist flexor tendon strains or the MNP from the torque experienced during pistol grip power tool operation. These findings would be useful to assess the potential development risk for tendonitis and CTS during such operations. Furthermore, the relative contributions of grip force and reaction torque towards the total strain in the tendons and the MNP are not known. Without these relationships, it is difficult for the ergonomists to implement safer work practices.

The purpose of this study was to quantify the flexor tendon strains and MNP during a typical pistol grip power tool operation used to secure threaded fasteners on an assembly line. The study intended to answer the following research questions: (a) what are the typical flexor tendon strains and MNP during pistol grip power tool operation; (b) what are the relative contributions of grip force and reaction torque on tendon strains and MNP? Additionally, this study also investigated the influence of wrist flexion angle and applied torque on these measurements.

2. Methods

The research methodology has been approved by the Office of Research Ethics at University of Waterloo. The present methodology used cadaveric specimens to simulate a hand–handle power tool operation with the wrist in the flexed, neutral and extended positions, while the MNP and strains in flexor tendons were measured.

CONTACT Naveen Chandrashekar nchandra@uwaterloo.ca

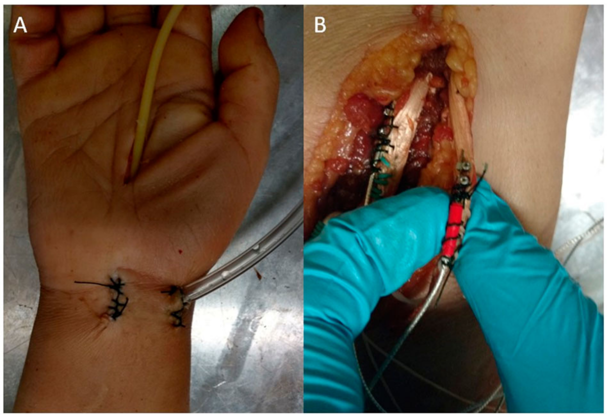

Figure 1. (A) Median nerve replacement tubing, surgical (opaque) and PVC (transparent). (B) FDP (left) and FDS (right) tendons with differential variable reluctance transducers.

Note: FDP = flexor digitorum profundus; FDS = flexor digitorum superficialis; PVC = polyvinyl chloride.

2.1. Specimen preparation

Six fresh-frozen cadaver arms (five right, one left) cut mid-humerus were procured for use in this study. The median age of the specimens was 52 years (range 39–54). The specimens did not have any reported upper-extremity injuries.

The arms were dissected to expose and isolate the wrist flexor and extensor tendons from their muscle bodies. Specifically, those muscle tendons providing the largest individual contributions to wrist stabilization during a maximum gripping task were exposed as described by Rossi et al. [17]. These included the tendons of the FDP, FDS, extensor digitorum communis (EDC), extensor carpi radialis brevis, extensor digitorum indicis, extensor pollicis longus and extensor carpi radialis longus. Tendons from the muscles that contribute to gripping but do not cross the wrist joint, such as the adductor pollicis oblique head and flexor pollicis brevis, were not exposed. Each of the five exposed tendons was sutured to a stainless-steel cable using surgical sutures. The FDS, FDP and EDC muscles each have four individual tendons that were sutured together to their individual cables.

2.2. Measurement of variables

The cadaver hand had to be instrumented to measure the strains in FDP and FDS tendons, the wrist flexion angle and the MNP. For this purpose, the FDS and FDP tendons were instrumented with a differential variable reluctance transducer (DVRT) (LORD Microstrain, USA) to measure strains in the tendons during experiments (Figure 1). An electrogoniometer (Biometrics Ltd, UK) was mounted on the cadaver wrist to measure the wrist flexion angle (Figure 2).

The MNP was measured using an approach similar to that of Keir et al. [14]. A small incision was made in the palm and proximal wrist to extract the median nerve. The nerve was replaced by thin-walled surgical tubing (diameter 4 mm) inserted retrograde from the palmar incision into the carpal tunnel [14]. This tubing was connected to sturdy polyvinyl chloride (PVC) tubing at the proximal entrance of the tunnel (Figure 1) and the system was sutured in place to prevent unwanted movement. Both tubes were filled with water and the distal end of the surgical tube was plugged with a small knot. The open end of the PVC tubing was connected to a pressure transducer (Model PX309-005G5 V; Omega, Canada) and the syringe was filled with water. The syringe was used to adjust the pressure to 57 mmHg, which has been documented as the resting pressure in the median nerve of patients with CTS [10].

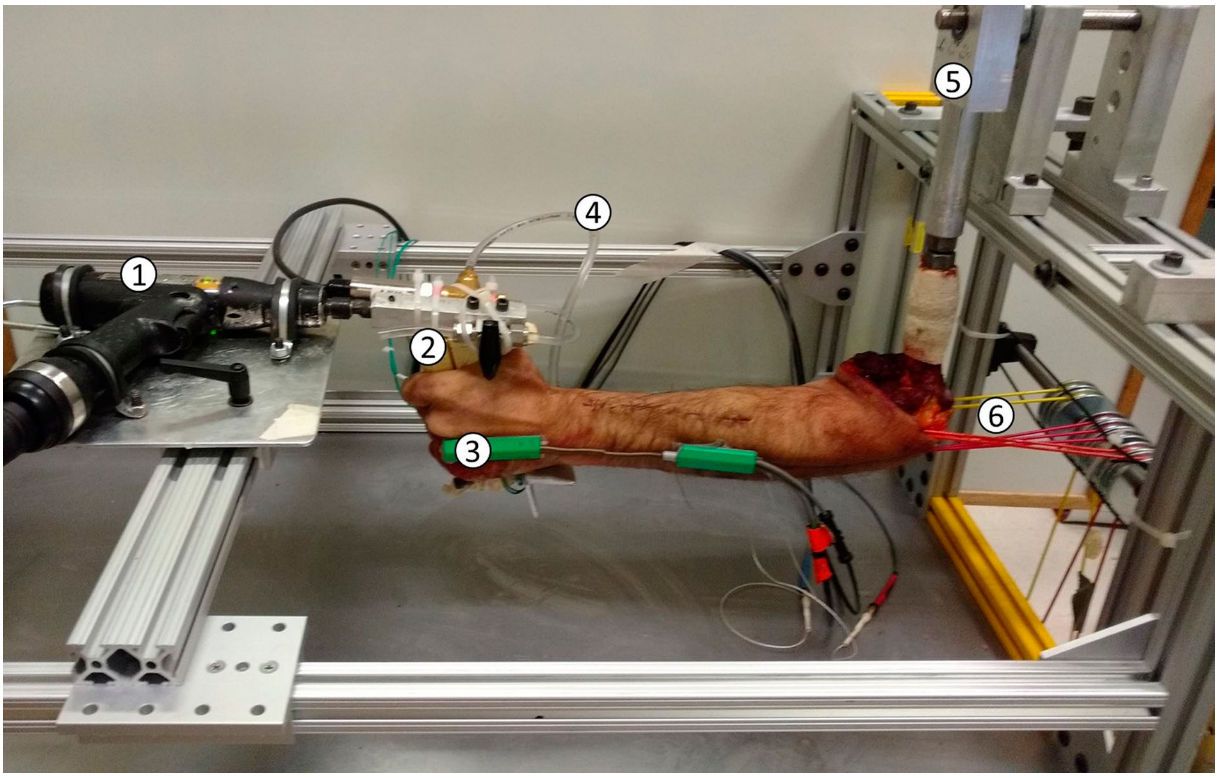

Figure 2. Custom-built hand simulator: (1) pistol grip power tool; (2) replica handle; (3) electrogoniometer; (4) MNP PVC tubing; (5) shoulder attachment; (6) muscle cables.

Note: MNP = median nerve pressure; PVC = polyvinyl chloride.

Table 1. Tendon forces.

Tendon	Force (N)
Flexor digitorum profundus	102
Flexor digitorum superficialis	45
Extensor digitorum communis	40
Extensor carpi radialis brevis	27
Extensor digitorum indicis	22
Extensor pollicis longus	22
Extensor carpi radialis longus	9

Figure 3. Pistol grip power tool.

2.3. Application of muscle forces using the hand simulator

The prepared specimen was then secured to the custom-built hand simulator (Figure 2). The shoulder joint was connected with a bearing to allow for shoulder abduction and screwed into the humerus with a 9.52-mm threaded rod. The length of the system from the bearing (point of rotation) to the elbow was measured to be 30 cm. The cables that were sutured to the exposed tendons were passed through a series of pullies posterior to the elbow and the weights were suspended from each cable to simulate muscle forces. The muscle forces applied to these tendons through weights are presented in Table 1 and were calculated using linear interpolation to find the muscle forces at 20% of the maximum gripping task forces for an elliptical handle, equivalent to 156 N of grip force [17].

2.4. Set-up for application of torque to the hand

The application of the muscle forces caused the specimen to grip a replica tool handle connected inline to the pistol grip power tool (Figure 3). The power tool was controlled by the Power Focus Controller (Atlas Corporation, Canada), which applied a 5-Nm torque when initiated through an external switch. The replica handle was created by taking a mould of the original handle and casting with a polyurethane resin (GoldenWest MFG, USA). The torque represented the loading profile of an M6 bolt being torqued on an automotive assembly line. It has been commonly reported that 5 Nm is a median torque value during pistol grip power tool use [29,30].

2.5. Torquing simulation trials

To facilitate the experiment, each bolt torquing simulation was broken into two phases: grip-only phase and grip-and-torque phase. During the grip-only phase, muscle forces were applied by suspending weights on the seven tendons causing the hand to grip the replica tool. The MNP and tendon strains were then measured. During the grip-and-torque phase, an external switch was used to engage the tool while the muscle forces were applied (and the tool was gripped). The tool rotated, causing the cadaver wrist (gripping the replica tool) to flex and the forearm to pronate, which were resisted by the muscle forces. Rotation continued until the tool registered 5 Nm of reactive torque. The MNP and tendon strains were measured during the torquing process. After each simulation, the hand was relaxed by unloading the weights from the tendons. The tool rotation angle, defined as the number of degrees the tool rotated after a baseline torque of 1 Nm, was recorded.

These simulations were completed with the wrist in three positions measured by the electrogoniometer: flexed (30°), neutral (−8°) [31] and extended (−30°) (Figure 4). The order of the wrist flexion angles was randomized, and each individual test was repeated six times for both phases resulting in a total of 36 trials per specimen.

2.6. Statistical analysis

Descriptive statistics were computed on the MNP and the FDP and FDS tendon strains for each specimen and the overall sample. The MNP and tendon strains were analysed using a non-parametric paired sign test to find the influence of phase, and non-parametric Friedman's two-way analysis of variance by ranks to find the influence on wrist flexion position [32]. An α value of 0.05 was used to test for significance during all tests. A Bonferroni correction factor was used during the Friedman test to correct for multiple comparisons. SPSS version 16.0 was used to conduct all statistical analyses.

3. Results

Simulations were successfully completed and both tendon strains and the MNP were obtained for all six specimens. The mean tool rotation angle was found to be 25.7° (*SD* 16.5°) and wrist flexion angles were found to increase during the trial by a mean of 3.2° (*SD* 3.7°). The torque–time curve of the pistol grip power tool during the grip-and-torque phase of each simulation is shown in Figure 5. The peak torque (5 Nm) occurred 360 ms after the tool was engaged.

3.1. Flexor digitorum profundus strain

During handle grip, the mean peak FDP strain was found to be 1.3% (*SD* 0.9%) and 1.5% (*SD* 0.9%) in the grip-only and the grip-and-torque phase, respectively (Figure 6). The signed test results revealed a statistically significant increase between the grip-only and the grip-and-torque phases ($p = 0.03$). Peak FDP tendon strains were not found to be affected by the wrist flexion angle ($p = 0.51$).

3.2. Flexor digitorum superficialis strain

The mean FDS strain during handle grip was 1.7% (*SD* 1.0%) for all three flexion angles. The mean FDS strain increased to 2.0% (*SD* 1.2%) with the torque applied (Figure 7). The grip-and-torque phase was found to have significantly larger FDS strain than the grip-only phase ($p = 0.03$) but no significance was found between flexion angles ($p = 0.12$).

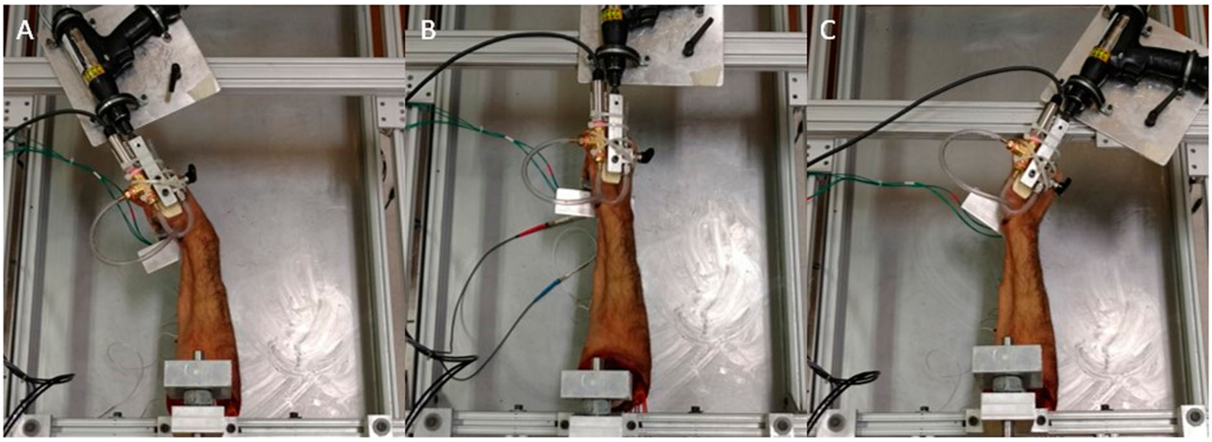

Figure 4. Wrist positions: (A) 30° flexion; (B) neutral; (C) 30° extension.

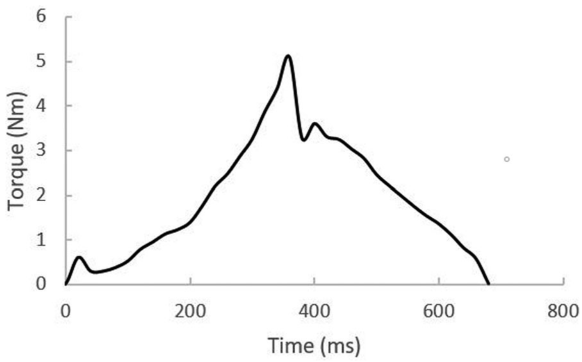

Figure 5. Torque–time curve for the bolt torquing simulation.
Note: Torque peaks at 360 ms.

3.3. Median nerve pressure

The increase in MNP during both phases at all three wrist positions is shown in Figure 8. Increase in MNP was found to be significantly correlated with increase in wrist flexion angle ($p < 0.01$). Bonferroni-corrected pairwise comparisons found that the flexed wrist position statistically increased the MNP over the extended position ($p < 0.01$). The differences between flexed and neutral positions or neutral and extended positions were not found to be statistically significant. Similar to the FDS and FDP strain analyses, the signed test revealed that the grip-and-torque phase significantly increased the MNP over the grip-only phase ($p = 0.03$).

4. Discussion

The typical values for flexor tendon strains and MNP during pistol grip power tool operation are not known. Quantifying these values throughout the wrist's range of motion may help researchers and ergonomists understand the risks of tendonitis and CTS during tool operation. In this study, a unique cadaveric methodology was used to investigate the effects of pistol grip power tool usage on the MNP and flexor tendon strains with three different wrist flexion angles. Conducting the simulation in two phases allowed for a separate investigation of the effect of gripping the tool and the applied torque. The main findings were: (a) the grip force accounts for the majority of tendon strain, since the addition of reactive torque results in a minimal but statistically significant strain increase; (b) the MNP is substantially higher during wrist flexion than extension. From the results, it appears that strategies to lower the grip force required to operate pistol grip power tools and improving wrist position angle may lower the incidence of cumulative trauma disorders.

4.1. Median nerve pressure

The influence of wrist flexion angle on the MNP was evident since the grip-and-torque phase increased the MNP by 15.3 mmHg when the wrist was flexed and only increased by 2.2 and 0.6 mmHg with a neutral and extended wrist position, respectively. The pressure increase during flexion was similar to the findings of Keir et al. [14], who found the MNP to increase by 12.5 mmHg when 39.2 N was applied to the finger flexors in a 30° flexed position. The results from the current study show a decrease in MNP in extension, which is in contrast with other findings. Many studies measuring carpal tunnel pressure show a parabolic relationship with carpal tunnel pressure increasing in both flexion and extension relative to the neutral position [14,27,33–35], whereas the work by McGorry et al. [36] found that pressure decreased as a function of increasing wrist flexion during a power grip task.

Keir et al. [14] indicated that the MNP measured by replacing the median nerve with thin-walled surgical tubing represents a combination of changes to the carpal tunnel pressure and contact stresses from the tendons. The increase in pressure in the flexed position using this technique is likely due to the wrapping of the flexor tendons through the carpal tunnel, which can compress the median nerve [27]. In extension, carpal tunnel pressure may increase but the flexor tendons pull towards the posterior aspect of the carpal tunnel, relieving contact with the median nerve.

The dangers of increased wrist flexion in the workplace are well documented. Wrist flexion is commonly included as a factor when evaluating the risk of injury [7,37]. However, the threshold MNP pressure that can cause these chronic injuries has not been investigated due to the difficulty in conducting long-term invasive clinical studies. Multiple studies have suggested that acute effects tend to occur when the carpal tunnel pressure is increased by 30 and 60 mmHg, which is also considered risky [38,39]. In the current study, flexing the wrist during pistol grip power tool operation increased the MNP by 15.8 mmHg, which would not cause acute damage to the nerve. This work demonstrates the MNP value that may be associated with prolonged pistol grip power tool operation in a flexed position. This may be a contributor to the incidence of CTS in the flexed position.

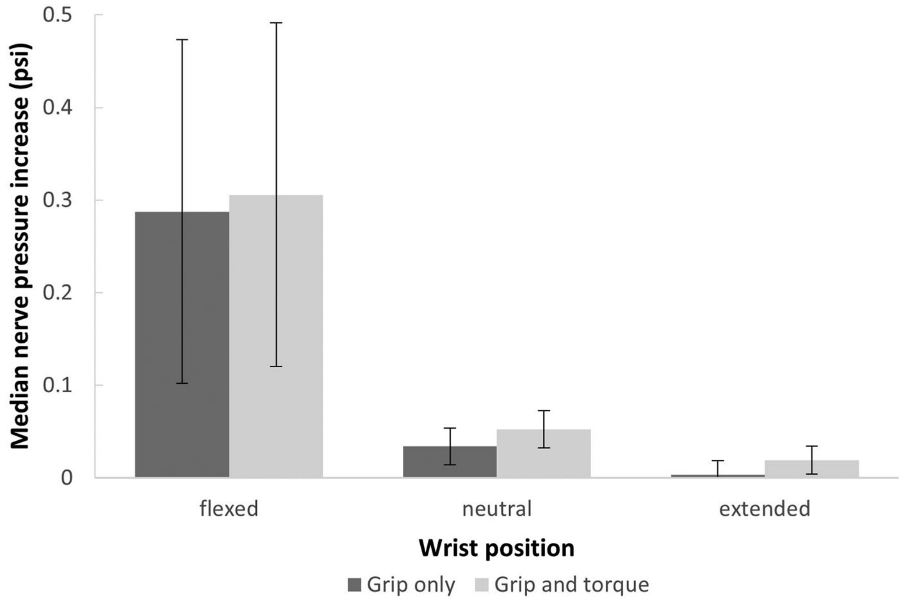

Figure 6. Median nerve pressure increase. Note: All results are the average result of the six specimens.

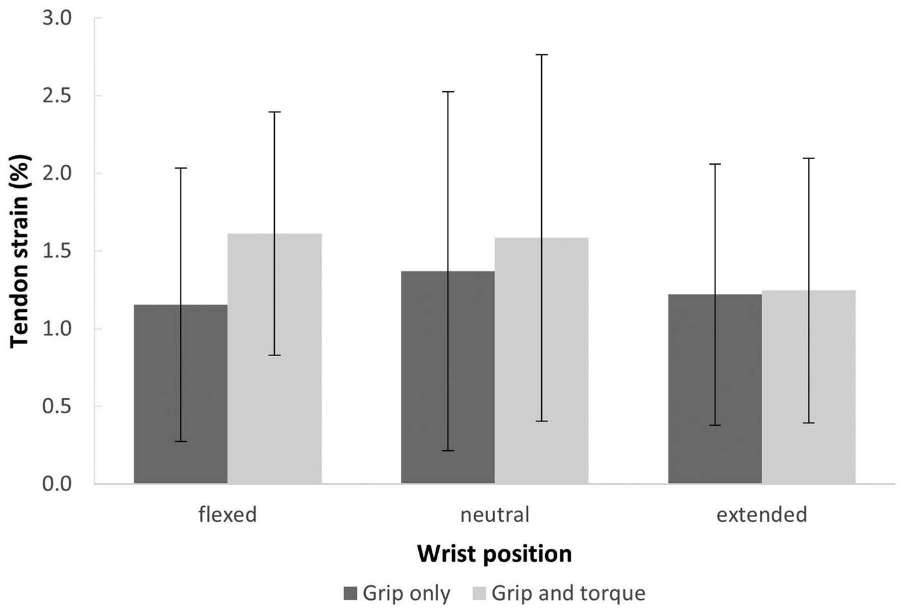

Figure 7. Flexor digitorum profundus strain. Note: All results are the average result of the six specimens.

The effects of rotational torque on the median nerve have not been previously investigated. The increase in MNP between the grip-only phase and the grip-and-torque phase was 0.9 mmHg. While this was a statistically significant increase in pressure, it is substantially smaller than the effect of wrist flexion. The dangers to the median nerve are more likely to be caused by gripping with a flexed wrist rather than by the rotational torque.

4.2. Tendon strains

The repeated tendon strains caused by gripping forces during pistol grip power tool operation are a suspected contributor to tendonitis [7,40]. However, it remains unknown whether these stresses are primarily caused by gripping or rotational torque from seating a bolt. The current study found that applying a rapid torque during the grip-and-torque phase increased the strain in the FDS tendon by 0.3% and in the FDP by 0.2%. This attributed to an increase between 5 and 30% of the total strain during the simulation. Therefore, while previous studies have related repetitive reaction torque to significant discomfort, this study concludes that it unlikely contributes to tendonitis in flexor tendons. Future studies should take into consideration the relative contributions of the FDS and FDP forces to create torques about the interphalangeal joints. The strains in these muscle groups may be subject to statistically significant differences and injury risk during the grip and torque phases. However, their differences were too small to be analysed during the current study.

The average peak FDP strain from the current study during the grip-only phase was 1.3% with 102 N grip force applied. This result is comparable to previously measured strains in the range of 0.2–1.8% during simulated grasping tasks with 80 N of applied load [16]. This work also found that significant creep can occur with repetitive cycling, increasing the strain by 40% by the 500th cycle. These results translated into the current

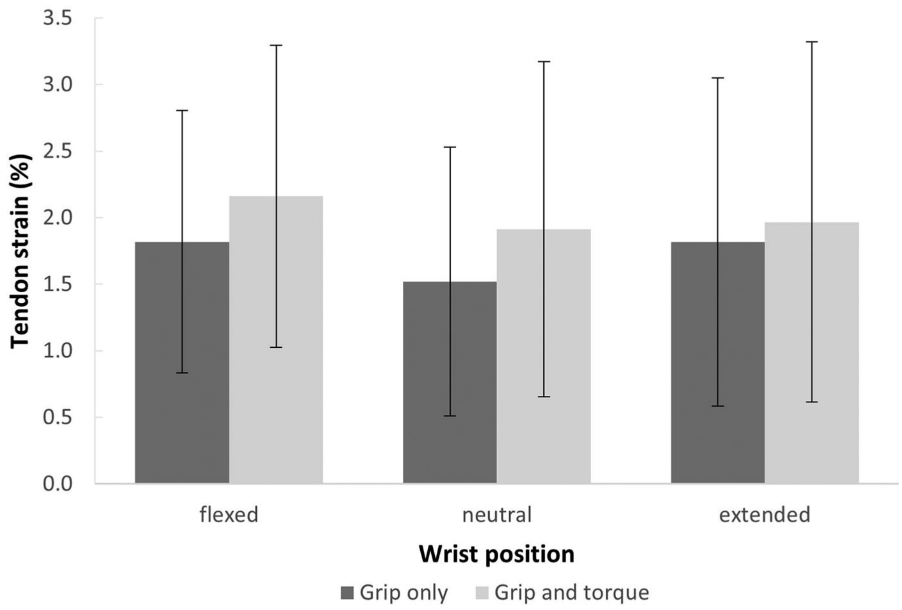

Figure 8. Flexor digitorum superficialis strain. Note: All results are the average result of the six specimens.

findings would indicate that the average peak FDP and FDS tendon strains could increase to 2.1 and 2.8%, respectively, under repetitive loading.

The in-vivo tendon strain threshold where fatigue loading becomes damaging is unknown [41]. The tendon strains found in this study are lower than the strains previously used to investigate microstructural changes associated with tendonitis. Fung et al. [42] found statistically significant area damage and morphological changes when rat tendons were fatigued to 6–7% strain. Legerlotz et al. [43] found that damage can occur after 5 h of cyclic loading at 30% of the failure strain. Both studies found microstructural damage associated with strains greater than those experienced during a bolt torquing action but with fewer cycles and a shorter time than an employee may experience during a career on a manufacturing line. However, the incidence of tendonitis associated with gripping forces during pistol grip power tool operation suggests that microstructural damage may happen when the flexor tendons are strained within the limits found in the current study. The tendon strain values found in this study could be used to find the number of cycles needed to cause microstructural damage at this strain level. This information could further be used to recommend a safe duration threshold for these power tools in order to prevent tendonitis.

These results suggest that strategies to reduce tendon forces, rather than lowering the transmitted torque, may be effective at lowering the incidence of tendonitis. Handle shape, diameter and torque duration have all been shown to have a significant effect on the required grip strength [17,40,44,45]. Tuning these parameters may allow a worker to apply lower muscle forces for the desired grip strength.

4.3. Limitations

There are limitations to this study. First, factors inherent to cadaveric research can affect the reliability of the results, including the effects of placement of the various sensors and difficulty in maintaining the anatomic alignment of the muscle forces. Second, the muscle forces used for this study were linearly scaled from a model developed for a maximal grip force application and not power tool usage. The distribution of muscle contribution to stabilizing the wrist may be different for power tool usage versus maximal grip. There may have been contributions from additional flexor muscles such as the flexor carpi radialis and flexor carpi ulnaris that were not included in this study. The results are limited to one activity with one set of operational parameters such as torque and grip force. The effects of variations of these parameters are not studied. Third, the effects of active insufficiency on muscle forces in the flexed position were not addressed due to no available muscle force models being found for this position. This position may change the muscle forces and strains through the FDP and FDS, which are known to be actively insufficient in this position.

5. Conclusion

The strain to the flexor tendons was between 1.5 and 2% and was mostly attributed to gripping the handle and not the reaction torque during the fastening action. Placing the wrist in a flexed position while using a pistol grip power tool dramatically increased the MNP. Strategies to lower the grip force required to operate pistol grip power tools and improving the wrist position angle may lower tendon strains and the MNP, and thereby the incidence of cumulative trauma disorders.

Disclosure statement

In accordance with Taylor & Francis policy and the authors' ethical obligation as researchers, they report receiving funding from Honda Canada Manufacturing, a company that may be affected by the research reported in the enclosed article. The authors have disclosed those interests fully to Taylor & Francis, and have in place an approved plan for managing any potential conflicts.

Funding

This work was supported by Honda Canada Manufacturing; Natural Science and Engineering Research Council of Canada [grant number: CRDPJ 511838-17]; Natural Sciences and Engineering Research Council of Canada.

References

[1] van Tulder M, Malmivaara A, Koes B. Repetitive strain injury. Lancet. 2007;369:1815–1822. doi:10.1016/S0140-6736(07)60820-4

[2] Lee I-H, Kim Y-K, Kang D-M, et al. Distribution of age, gender, and occupation among individuals with carpal tunnel syndrome based on the national health insurance data and national employment insurance data. Ann Occup Environ Med. 2019;31:e31. doi:10.35371/aoem.2019.31.e31
[3] Harris-Adamson C, Eisen EA, Kapellusch J, et al. Biomechanical risk factors for carpal tunnel syndrome: a pooled study of 2474 workers. Occup Environ Med. 2015;72(1):33–41. doi:10.1136/oemed-2014-102378
[4] Marcum J, Adams D. Work-related musculoskeletal disorder surveillance using the Washington state workers' compensation system: recent declines and patterns by industry, 1999–2013. Am J Ind Med. 2017 May;60(5):457–471. doi:10.1002/ajim.22708
[5] Maghsoudipour M, Moghimi S, Dehghaan F, et al. Association of occupational and non-occupational risk factors with the prevalence of work related carpal tunnel syndrome. J Occup Rehabil. 2008 Jun;18(2):152–156. doi:10.1007/s10926-008-9125-4
[6] Bao S, Howard N, Lin J-H. Are work-related musculoskeletal disorders claims related to risk factors in workplaces of the manufacturing industry? Ann Work Expo Heal. 2020;64(2):152–164. doi:10.1093/annweh/wxz084
[7] Garg A, Moore JS, Kapellusch JM. The revised strain index: an improved upper extremity exposure assessment model. Ergonomics. 2017;60(7):912–922. doi:10.1080/00140139.2016.1237678
[8] Keir PJ, Farias Zuniga A, Mulla DM, et al. Relationships and mechanisms between occupational risk factors and distal upper extremity disorders. Hum Factors. 2021 Feb;63(1):5–31. doi:10.1177/0018720819860683
[9] Barr AE, Barbe MF, Clark BD. Work-related musculoskeletal disorders of the hand and wrist: epidemiology, pathophysiology, and sensorimotor changes. J Orthop Sports Phys Ther. 2004 Oct;34(10):610–627. doi:10.2519/jospt.2004.34.10.610
[10] Okutsu I, Hamanaka I, Chiyokura Y, et al. Intraneural median nerve pressure in carpal tunnel syndrome. J Hand Surg Br. 2001 Apr 7;26(2):155–156. doi:10.1054/jhsb.2000.0534
[11] Cobb TK, An KN, Cooney WP. Externally applied forces to the palm increase carpal tunnel pressure. J Hand Surg Am. 1995 Mar;20(2):181–185. doi:10.1016/S0363-5023(05)80004-8
[12] Palmer KT, Harris EC, Coggon D. Carpal tunnel syndrome and its relation to occupation: a systematic literature review. Occup Med (Chic Ill). 2006;57(1):57–66. doi:10.1093/occmed/kql125
[13] Cowley JC, Leonardis J, Lipps DB, et al. The influence of wrist posture, grip type, and grip force on median nerve shape and cross-sectional area. Clin Anat. 2017;30(4):470–478. doi:10.1002/ca.22871
[14] Keir PJ, Wells RP, Ranney DA, et al. The effects of tendon load and posture on carpal tunnel pressure. J Hand Surg Am. 1997 Jul;22(4):628–634. doi:10.1016/S0363-5023(97)80119-0
[15] White KM, Congleton JJ, Pendleton OJ, et al. Defending the wrist deviation test for carpal tunnel syndrome screening: a comparison of vibration thresholds and distal motor latency. Int J Occup Saf Ergon. 1996;2(4):315–335. doi:10.1080/10803548.1996.11076360
[16] Goldstein SA, Armstrong TJ, Chaffin DB, et al. Analysis of cumulative strain in tendons and tendon sheaths. J Biomech. 1987;20(1):1–6. doi:10.1016/0021-9290(87)90261-2
[17] Rossi J, De Monsabert B G, Berton E, et al. Handle shape affects the grip force distribution and the muscle loadings during power grip tasks. J Appl Biomech. 2015 Dec;31(6):430–438. doi:10.1123/jab.2014-0171
[18] Muggleton JM, Allen R, Chappell PH. Hand and arm injuries associated with repetitive manual work in industry: a review of disorders, risk factors and preventive measures. Ergonomics. 1999 May;42(5):714–739.
[19] Yoshii Y, Zhao C, Zhao KD, et al. The effect of wrist position on the relative motion of tendon, nerve, and subsynovial connective tissue within the carpal tunnel in a human cadaver model. J Orthop Res. 2008 Aug;26(8):1153–1158. doi:10.1002/jor.20640
[20] Baechler MF, Means KR, Parks BG, et al. Carpal canal pressure of the distracted wrist. J Hand Surg Am. 2004 Sep;29(5):858–864. doi:10.1016/j.jhsa.2004.04.018
[21] Farr LD, Werner FW, McGrattan ML, et al. Wrist tendon forces with respect to forearm rotation. J Hand Surg Am. 2013 Jan;38(1):35–39. doi:10.1016/j.jhsa.2012.10.012
[22] Werner FW, Palmer AK, Somerset JH, et al. Wrist joint motion simulator. J Orthop Res. 1996 Jul;14(4):639–646. doi:10.1002/jor.1100140420
[23] Kataoka T, Moritomo H, Omori S, et al. Pressure and tendon strain in the sixth extensor compartment of the wrist during simulated provocative maneuvers for diagnosing extensor carpi ulnaris tendinitis. J Orthop Sci. 2015;20(6):993–998.
[24] Pensy RA, Brunton LM, Parks BG, et al. Single-incision extensile volar approach to the distal radius and concurrent carpal tunnel release: cadaveric study. J Hand Surg Am. 2010 Feb;35(2):217–222. doi:10.1016/j.jhsa.2009.11.011
[25] Jernigan 3rd EW, Smetana BS, Rummings WA, et al. The Effect of intraoperative glove choice on carpal tunnel pressure. J Hand Microsurg. 2020 Apr;12(1):3–7.
[26] Engles ML, Donatelli RA, Glasheen-Way M. Pressure changes in the carpal tunnel with movement of the pisiform bone. J Orthop Sports Phys Ther. 1982;4(1):47–50. doi:10.2519/jospt.1982.4.1.47
[27] Vignais N, Weresch J, Keir PJ. Posture and loading in the pathomechanics of carpal tunnel syndrome: a review. Crit Rev Biomed Eng. 2016;44(5):397–410. doi:10.1615/CritRevBiomedEng.2017021073
[28] Goislard de Monsabert B, Rossi J, Berton E, et al. Quantification of hand and forearm muscle forces during a maximal power grip task. Med Sci Sports Exerc. 2012 Oct;44(10):1906–1916. doi:10.1249/MSS.0b013e31825d9612
[29] Freivalds A, Eklund J. Reaction torques and operator stress while using powered nutrunners. Appl Ergon. 1993 Jun;24(3):158–164. doi:10.1016/0003-6870(93)90003-R
[30] Oh S, Radwin RG. Pistol grip power tool handle and trigger size effects on grip exertions and operator preference. Hum Factors. 1993;35(3):551–569. doi:10.1177/001872089303500311
[31] Fagarasanu M, Kumar S, Narayan Y. Measurement of angular wrist neutral zone and forearm muscle activity. Clin Biomech (Bristol, Avon). 2004 Aug;19(7):671–677. doi:10.1016/j.clinbiomech.2004.05.004
[32] Elias JJ, Faust AF, Chu YH, et al. The soleus muscle acts as an agonist for the anterior cruciate ligament. An *in vitro* experimental study. Am J Sport Med. 2003;31(2):241–246. doi:10.1177/03635465030310021401
[33] Keir PJ, Bach JM, Hudes M, et al. Guidelines for wrist posture based on carpal tunnel pressure thresholds. Hum Factors J Hum Factors Ergon Soc. 2007;49(1):88–99. doi:10.1518/001872007779598127
[34] Keir PJ, Bach JM, Rempel DM. Effects of finger posture on carpal tunnel pressure during wrist motion. J Hand Surg Am. 1998;23(6):1004–1009. doi:10.1016/S0363-5023(98)80007-5
[35] Seradge H, Jia YC, Owens W. *In vivo* measurement of carpal tunnel pressure in the functioning hand. J Hand Surg Am. 1995;20(5):855–859. doi:10.1016/S0363-5023(05)80443-5
[36] McGorry RW, Fallentin N, Andersen JH, et al. Effect of grip type, wrist motion, and resistance level on pressures within the carpal tunnel of normal wrists. J Orthop Res. 2014 Apr;32(4):524–530. doi:10.1002/jor.22571
[37] Moore JS, Garg A. The Strain Index: a proposed method to analyze jobs for risk of distal upper extremity disorders. Am Ind Hyg Assoc J. 1995 May;56(5):443–458.
[38] Lundborg G, Gelberman RH, Minteer-Convery M, et al. Median nerve compression in the carpal tunnel – functional response to experimentally induced controlled pressure. J Hand Surg Am. 1982 May;7(3):252–259. doi:10.1016/S0363-5023(82)80175-5
[39] Weresch JA, Keir PJ. Development of an ergonomic tool to predict carpal tunnel syndrome risk based on estimated carpal tunnel pressure. IISE Trans Occup Ergon Hum Factors. 2018;6(1):32–42. doi:10.1080/24725838.2018.1454360
[40] Kong YK, Kim DM. The relationship between hand anthropometrics, total grip strength and individual finger force for various handle shapes. Int J Occup Saf Ergon. 2015;21(2):187–192. doi:10.1080/10803548.2015.1029726
[41] Shepherd JH, Screen RC. Fatigue loading of tendon. Int J Exp Pathol. 2013 Aug;94(4):260–270.
[42] Fung DT, Wang VM, Laudier DM, et al. Subrupture tendon fatigue damage. J Orthop Res. 2009 Feb;27(2):264–273.
[43] Legerlotz K, Jones GC, Screen HRC, et al. Cyclic loading of tendon fascicles using a novel fatigue loading system increases interleukin-6 expression by tenocytes. Scand J Med Sci Sports. 2013 Feb;23(1):31–37.
[44] Rossi J, Berton E, Grélot L, et al. Characterisation of forces exerted by the entire hand during the power grip: effect of the handle diameter. Ergonomics. 2012;55(6):682–692. doi:10.1080/00140139.2011.652195
[45] Radwin RG, VanBergeijk E, Armstrong TJ. Muscle response to pneumatic hand tool torque reaction forces. Ergonomics. 1989;32(6):655–673. doi:10.1080/00140138908966140