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Survey-based identification of design requirements and constraints for a wearable tremor suppression device

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Abstract

Introduction: Parkinsonian tremor has severely impacted the lives of 65% of individuals with Parkinson's disease, and nearly 25% do not respond to traditional treatments. Although wearable tremor suppression devices (WTSDs) have become a promising alternative approach, this technology is still in the early stages of development, and no studies have reported the stakeholders' opinions on this technology and their desired design requirements.

Methods: An online survey was distributed to affected Canadians and Canadian movement disorder specialists (MDS) to acquire information on demographics, the current state of treatments, opinions on the WTSDs, and the desired design requirements of future WTSDs.

Results: A total of 101 affected individuals and 24 MDS completed the survey. It was found that both groups are generally open to using WTSDs to manage tremor. The most important design requirement to end users is the adaptability to lifestyle, followed by weight and size, accurate motion, comfort, safety, quick response, and cost. Lastly, most of the participants (65%) think that the device should cost under $500.

Conclusions: The findings from this study can be used as guidelines for the development of future WTSDs, such that the future generations could be evaluated and accepted by the end users.

Keywords

Wearable tremor suppression device, Parkinson's disease, movement disorder, medical informatics, survey, design requirements

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Introduction

Parkinson's disease (PD) is a progressive neurological disorder that affects 1 in 500 people in Canada. Currently, nearly 100,000 Canadians are living with PD.[1] As the population in Canada grows and ages, it is predicted that the overall number will double in the next 20 years.[2,3] The progressive and chronic nature of PD leads to a substantial economic burden on individual patients and the health care systems.[4,5] It is estimated that the economic burden of PD in Canada is more than $1.2 B in direct and indirect costs associated with the disease.[3] Tremor is one of the most disabling symptoms of PD, and affects about 65% of people living with PD.[6] The existence of tremor can result in individuals experiencing limitations of physical functions, emotional stress, and social isolation, which may significantly compromise their quality of life.[7]

Medication and brain surgery are the mainstays of treatment for parkinsonian tremor.[8,9] However, it has been reported that medication provides a suboptimal benefit to 25% of the individuals living with parkinsonian tremor. Furthermore, medication often presents side effects and issues with drug tolerance.[10] Although brain surgery is often very effective in managing tremor, it carries a risk of significant complications for the individual,[11] and is only considered for those individuals with advanced PD (less than 2% of the PD population[12]). As an alternative, research in wearable tremor suppression devices (WTSD, Figure 1) has been facilitated by the development of wearable technology.

For the past two decades, many WTSDs have been developed and validated. These devices suppress tremor by applying external controllable stimulations on the target joint(s) or the muscles that actuate the target joint(s), such as mechanical loading[13–27] and electrical stimulation.[28–39] The validation of these devices has proven their feasibility for suppressing tremor, with reported tremor suppression ratios ranging from 40% to 95.2%.[40] Although these technologies have shown promising results, none of these WTSDs have become commercially available. Furthermore, very few of them have even been evaluated in the clinic. Other than the hurdles presented in the commercialization process, the lack of acceptance by the stakeholders may be caused by several factors, such as size, weight, discomfort, safety, cost, performance when suppressing tremor, adaptability to the user's lifestyle, or inadequate knowledge of this technology among the stakeholders. Whether these factors contribute to the lack of acceptance of WTSDs is an important question to be answered; however, no existing studies have responded to this question. Hence, in order to facilitate the acceptance of WTSDs by clinicians and individuals with PD, it is imperative to understand why the current WTSDs are not widely used, and what aspects of a WTSD are considered to be the most important to the stakeholders.

In view of the identified gaps in the field of wearable tremor suppression technology, the primary goal of this study was to survey individuals with PD and movement disorder specialists (MDS) to understand their opinions and expectations about WTSDs. The secondary goal was to obtain the user-centered design requirements for future WTSDs. The objectives of this study include the identification of the obstacles to the acceptance of the current WTSDs by the stakeholders, and the establishment of guidelines for future research in the development and evaluation of WTSDs.

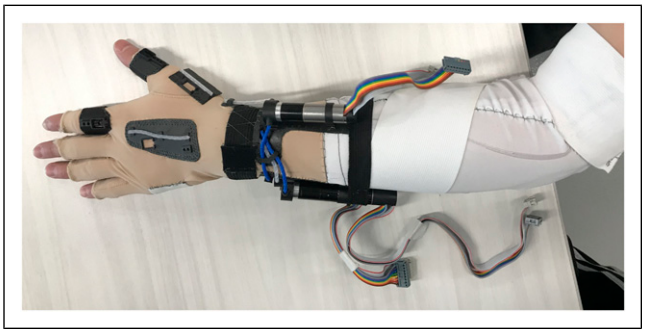

Figure 1. A wearable tremor suppression glove developed in.[13] It suppresses tremor in the index finger, the thumb, and the wrist using mechanical loading.

The rest of the article is organized as follows: in *Methods*, the survey design, participant recruitment, and data analysis methods are described. *Results* presents the findings of the survey. The outcomes of the survey study are discussed in *Discussion*. The last section presents a summary of this study.

Methods

This paper presents findings from an analysis of quantitative data collected from an online survey of people with PD and MDS in Canada, exploring the current state of parkinsonian tremor management in Canada, the stakeholders' opinions on the tremor management approaches and WTSDs, and the desired design requirements of future WTSDs. The survey was developed based on the guidelines for the design of questionnaires for survey research.[41] The presentation of this paper follows the Checklist for Reporting Results of Internet E-Surveys (CHERRIES).[42] The study protocol was approved by the University of Western Ontario's Human Research Ethics Board (Protocol no. 112194, approved on March 19, 2020).

Survey Design

The online survey was developed and conducted using Qualtrics XM. It contains two self-administered questionnaires (See Appendix) that include a mixture of open ended and multiple–choice questions. The questionnaire for the MDS participants includes a total of 13 questions, two of which were open ended, and 11 were multiple choice questions, asking the participants to provide information

about their experience when treating parkinsonian tremor and their opinions on the use of a WTSD. The questionnaire for the participants with PD includes a total of 17 questions, one of which was an open ended question, and 16 were multiple–choice questions, asking the participants to provide their demographic information (including age, sex, years since PD diagnosis), received treatments, and their opinions on the treatments and WTSDs. The participants from both groups were also asked to rank the aspects of a WTSD they consider important. Prior to opening the survey, preliminary runs were conducted by one person with PD, one movement disorders specialist, and four research collaborators to detect flaws, ambiguity, and missing questions/answers of interest.

Recruitment and data collection

People who were diagnosed with PD and capable of completing an online survey were invited to participate in the study from April 2020 to March 2021. As there is no national database of individuals with PD, a Google search was performed to identify the Parkinson's societies, associations, and support groups in each province. The coordinator of each identified organization was contacted via email for distribution of the survey. Upon completing the screening of the study by each organization, the survey was sent out to individuals with PD via weekly newsletter and was posted on the webpage of each organization. Both the newsletter and the online poster contained a link to the survey, where a letter of information and a consent form were displayed before the questionnaire. Note that no description of WTSDs was given to the participants before they participated in this survey. The participants with PD were not administered any cognitive tests since these tests must be conducted in person. By continuing to the questionnaire, the participant agreed to give consent to enroll; and by navigating and completing the questionnaire, it was considered that the participants with PD were able to answer the questions.

In addition to the participants with PD, MDS with a practice focus on PD were invited to participate in the study from August 2020 to May 2021. The contact information of MDS was identified on the Canadian Movement Disorder Group, as it has a public internet database of MDS in Canada, which can be searched by area of practice. A total of 61 MDS with a PD focus to their practice were identified for recruitment. Recruitment was conducted through direct email invitation. A total of six reminder emails were sent out after the initial contact. Each email contained a link to the survey, where a letter of information and a consent form were displayed before the questionnaire. By continuing to the questionnaire, the participant agreed to give consent to enroll.

Participation in this study was completely voluntary. The participants from both groups were not offered any incentives to complete the questionnaire. Since the recruitment of people with PD relied on the distribution of the survey by each Parkinson's association, the survey response rate could not be calculated traditionally based on the number of invitations and respondents. As an alternative, the completion rate was used for the participants with PD, i.e., the ratio of users who finished the survey versus users who completed the consent page. As for the MDS respondents, the response rate was calculated as the ratio of the number of responses versus the number of invitations. Lastly, an IP check was enabled in the survey to prevent duplicate entries by the same user.

Data analysis

The survey responses were analyzed using the IBM Statistical Package for Social Science (SPSS version 24) statistics software. Descriptive statistics and frequency counts were used to present the obtained data, and cross-tabulation analysis was used to examine potential associations between different variables. Since these variables are ordinal data, the Gamma test was used for the cross-tabulation analysis between the independent variables and the response variables, and the Somers' Delta test was used for the explanatory variables and the response variables. As for the numerical ranking questions, Friedman's ANOVA test was used to assess whether the ranking result rejects the null hypothesis of equal mean ranks. Furthermore, Kendall's W test was used to quantify the agreement among the respondents on these ranking questions. The α was set to 0.05, and an 80% power was used.

Results

In this section, the results obtained from the respondents with PD are reported in the first subsection. The second subsection presents the results obtained from the MDS respondents.

Respondents with PD

Demographics and opinions on received treatments. A total of 110 individuals with PD responded to the survey, of which 101 completed the survey and 9 did not (the completion rate was 91.8%). The majority of the respondents were between 50 and 79 years old (98, 97%), with only one above 80 years old (1%) and two under 50 years old (2%). Respondents had been diagnosed with PD for 5.2 ± 3.9 years (range from 1 to 25 years). The male-to-female ratio of the entire respondent group is 1.3:1.0 (57/44). Among the respondents who completed the survey, all respondents are currently using medication as treatment for managing upper-limb tremors; 3 (3%) are using deep brain stimulation (DBS); and 3 (3%) are using exercise. Note that the respondents who are currently using DBS and exercise are also taking medication. The detailed demographics of the respondents with PD are shown in Table 1.Table 2 presents the opinions of the respondents with PD on the treatments that they are currently receiving to

suppress tremors. A total of four aspects of the treatments were questioned, which were the Effectiveness of the treatment on managing tremor, the cost of the treatment, the side effects, and the difficulty of managing treatment in daily life. The highest-ranked answers regarding the participants' opinions on their current treatments are that they are effective at managing their symptoms (46, 45.5%), affordable (68, 67.4%), with side effects (39, 38.6%), and are easy to manage in daily life (67, 66.4%); while 30 (29.7%) considered them ineffective, 7 (6.9%) considered them expensive, 34 (33.7%) without side effects, and 7 (6.9%) found the treatment hard to manage in daily life; the rest of the cohort felt the treatments were neither effective nor ineffective (25, 24.8%), neither affordable nor expensive (26, 25.7%), neither with nor without side effects (28, 27.7%), and neither easy nor hard to manage (27, 26.7%). These selections are herein defined as "neutral". Among the respondents who are receiving medication, 31 (30.7%) consider medication to not be effective in managing their tremor, 7 (6.9%) experience inconsistency in the effectiveness of medication, 41 (40.6%) reported the effect of medication wears off quickly, 38 (37.6%) experience side effects, 1 (1%) forgot to take the medicines in the past, and only 8 (7.9%) have not experienced any difficulties with medication.

Lastly, among the three respondents who have undergone brain surgery, 2 (66.7%) are not satisfied with the improvement of their symptoms, 2 (66.7%) had complications due to surgery, and 1 (33.3%) has difficulty with the maintenance of the DBS device.

Table 1. Demographics of the respondents with PD.

Characteristics	Individuals with PD (N = 101), n (%)
Age range	
Under 30	0 (0%)
30–39	0 (0%)
40–49	2 (2%)
50–59	25 (24.7%)
60–69	43 (42.6%)
70–79	30 (29.7%)
Above 80	1 (1%)
Sex	
Female	44 (43.6%)
Male	57 (56.4%)
Treatment	
Medication†	101 (100%)
DBS	3 (3%)
Other treatments‡	3 (3%)
No treatment	0 (0%)
Years since diagnosis (Mean ± Standard Deviation): 5.2 ± 3.9	

†Also includes individuals who received both medication and brain surgery.
‡Includes exercise and assistive devices.

Knowledge and opinions on WTSDs. Participants' knowledge and opinions on WTSD are one of the primary outcomes examined. Table 3 presents the descriptive statistics of their knowledge and opinions on WTSDs. It was found that most respondents were not informed about WTSDs from their primary doctor (99, 98%), nor have they participated in WTSD-related studies (98, 97%). Although most of the respondents did not acquire information about WTSDs from their primary doctors, 29 (28.7%) of the respondents reported that they had heard the concept of the WTSD, 16 (15.8%) have seen WTSDs on the news, 1 (1%) has studied WTSD-related literature, and 2 (2%) have been actively participating in a WTSD-related study. Overall, 48 (47.5%) of the respondents are aware of WTSDs and 53 (52.5%) are not.

In general, personal opinions are directly affected by knowledge of the examined subject. In this study, it was found that most of the respondents have little knowledge of WTSDs; however, their opinions on the concept of a WTSD are mostly positive (68.3%, 69/101). 29 (28.7%) felt uncertain about the concept of using WTSD to treat parkinsonian tremor and only 3 (3%) felt that the WTSDs would not improve upon their current treatment. Although the

Table 2. Opinions of the individuals with PD on the received treatments.

Opinion on the received treatments (N = 101)	Outcomes, n (%)		
Effectiveness of the treatment for managing tremor	Effective: 46 (45.5%)	Ineffective: 30 (29.7%)	Neutral: 25 (24.8%)
Cost of the treatment	Affordable: 68 (67.4%)	Expensive: 7 (6.9%)	Neutral: 26 (25.7%)
Side effects	w/o side effects: 34 (33.7%)	w/side effects: 39 (38.6%)	Neutral: 28 (27.7%)
Difficulty of managing treatment in daily life	Easy to manage: 67 (66.4%)	Hard to manage: 7 (6.9%)	Neutral: 27 (26.7%)
Difficulties with medication (N = 101), n (%)†			
Not effective for tremor	31 (30.7%)	Side effects	38 (37.6%)
Inconsistent effectiveness for tremor	7 (6.9%)	Forgot to take the medicine	1 (1%)
Effect wears off quickly	41 (40.6%)	No difficulties	8 (7.9%)
Difficulties with brain surgery (N = 3), n (%)			
Surgical complications	2 (66.7%)	Maintenance of the DBS device	1 (33.7%)
Symptoms did not improve as expected	2 (66.7%)		

†Also includes the individuals who received both medication and brain surgery.

Table 3. Knowledge and opinions of the individuals with PD on WTSDs.

Primary doctor has provided information of WTSD		Yes: 2 (2%)
Participated in WTSD-related study		Yes: 3 (3%)
Knowledge of WTSD	Aware of WTSD: 48 (47.5%)	Actively participating in related research study: 2 (2%) Have studied related literature: 1 (1%) Read on news: 16 (15.8%) Heard of the concept: 29 (28.7%)
	Not aware of WTSD	Not aware of it: 53 (52.5%)
Opinion on the concept of WTSD	Positive: 69 (68.3%)	Excellent idea: 34 (33.7%) Good idea: 35 (34.6%)
	Uncertain	29 (28.7%)
	Negative	Would not be an improvement over current treatment 3 (3%)
Opinion on trying a WTSD	Positive: 47 (46.5%)	Very strongly: 24 (23.7%) Fairly strongly: 23 (22.8%)
	Uncertain	40 (39.6%)
	Negative: 10 (9.9%)	I am happy with my current treatment: 7 (6.9%) Not interested: 3 (3%)
	Did not answer this question: 4 (4%)	
Preference of tremor management methods[‡]		Top: Medication, Mid: WTSD, Least: brain surgery (DBS)

‡$p < .05$, Kendall's W = .576.

respondents' opinions on the concept of WTSD are generally positive, less enthusiasm was found among the respondents when they were asked about trying a WTSD. Only 47 (46.5%) rated strongly in favor of trying a WTSD, 40 (39.6%) would have to see the design first, 10 (9.9%) are either not interested or are happy with their current treatment, and 4 (4%) did not answer this question.

Lastly, the respondents reported that medication is their most favored treatment, followed by WTSD, and brain surgery (DBS). The Kendall's W test on the ranking results found a high variability (37.9%, i.e., Kendall's W = 0.621) on the ranking, indicating that not every respondent agreed on the answer; however, the Friedman's ANOVA test rejected the null hypothesis of equal mean ranks ($p < .05$), which indicates that a statistically-significant similarity in the ranking answers was found to represent the opinion of the group.

Influencing factors of the opinions on WTSDs. Figure 2 shows the influence of nine factors, which include three independent variables and six explanatory variables, on the participants' opinions about WTSDs, including two response variables. The quantified influence of the nine factors on the two response variables is divided into two columns (Figure 2(a)). The subplots in the left column present the influence of the nine factors on the participants' opinions about the concept of WTSDs in general, and the subplots in the right column present the influence of the nine factors on the participants' opinions on trying a WTSD.

The independent variables are age (a and b), year since diagnosis (c and d), and sex (e and f). Note that the number of the respondents under the age of 50 and above the age of 80 accounts for only 3% (3/101) of the entire cohort. The respondents under the age of 50 and those between 50 and 59 years old were grouped together, i.e., age under 60, for cross-tabulation analysis. Similarly, an age group above 70 years old was created by combining the respondents from the age group between 70 and 79 years, and above 80 years. The explanatory variables include their awareness of WTSDs (g and h), the overall satisfaction of the treatment they currently receive (i and j), the Effectiveness of their current treatment on managing tremor (k and l), the difficulty of managing treatment in daily life (m and n), the side effects of their current treatment (o and p), and the cost of their current treatment (q and r). Note that the year since diagnosis was categorized into three groups based on a time range of five years,[43,44] i.e., 0–5 years, 5–10 years, and above 10 years; the overall satisfaction of the treatment was categorized into two groups, i.e., satisfied and unsatisfied. A respondent was placed into the satisfied group only when none of the four aspects of the treatments were rated as negative. The descriptive statistics are shown by the bar graphs (Figure 2(a)), and the statistical association between each influencing factor and each response variable is shown by the color map in Figure 2(b).

The y axis of each bar graph in Figure 2(a) shows the frequency count, and the x axis shows the options of each independent/explanatory variable. Note that each option on the x axis contains three bars that indicate the answers, i.e., positive

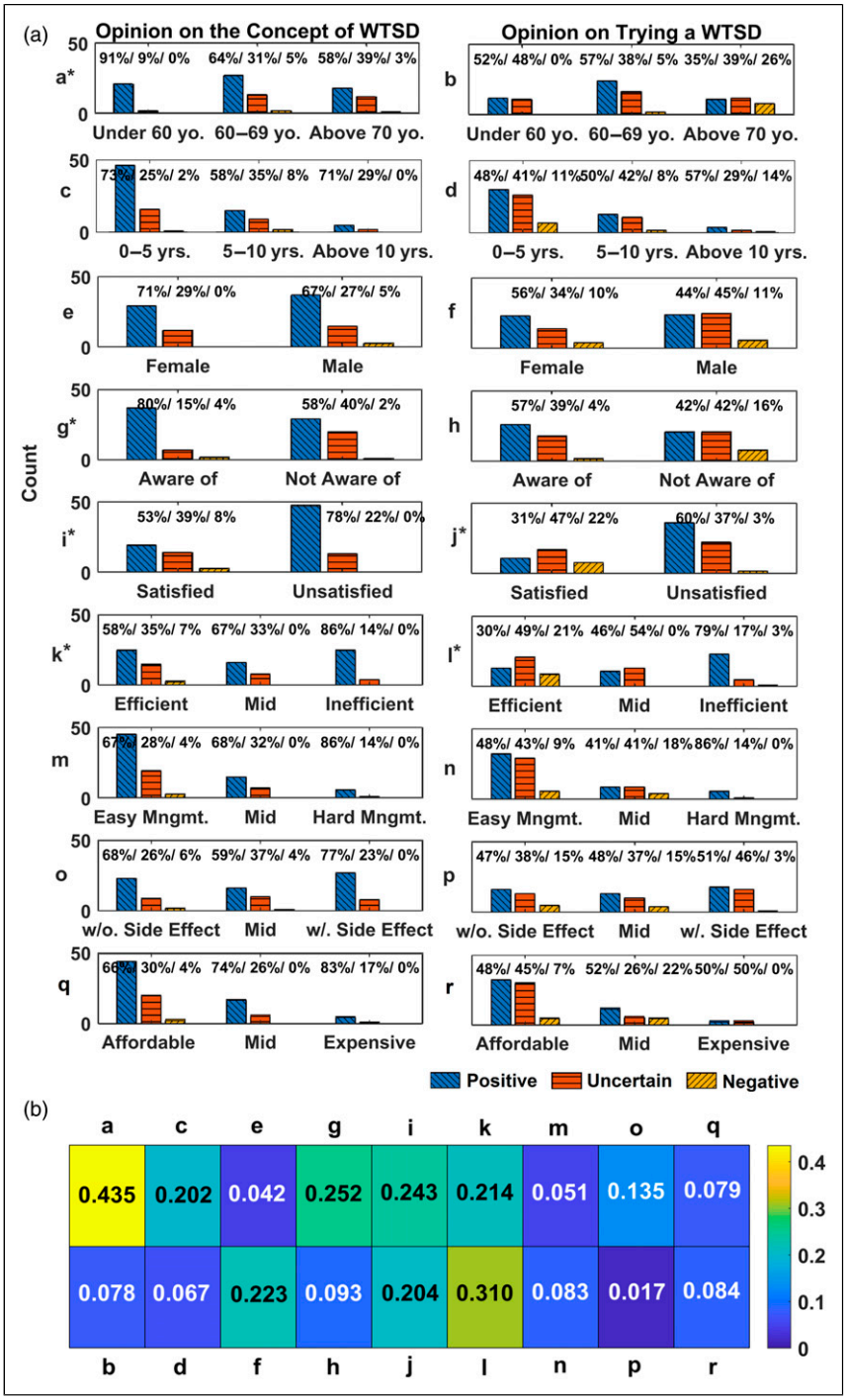

Figure 2. Influence of nine factors on the opinions of the individuals with PD on WTSDs. a. Each row presents the quantified influence of each factor on the participants' opinions on the concept of WTSDs (Left) and the opinions on trying a WTSD (Right). The first row represents the factor age, followed by the year since diagnosis, sex, their awareness of WTSDs, the overall satisfaction with their current treatment, the Effectiveness of their current treatment on managing tremor, the difficulty of managing treatment in daily life, the side effects of their current treatment, and the cost of their current treatment. The *y* axis of each bar graph shows the frequency count, and the *x* axis shows the options of each independent/explanatory variable. The numbers above each set of bar graphs present the percentage distribution of the answers. The factors that statistically associate ($p < .05$) with the opinions on the WTSDs are labeled by "*". b. The cell colors and the numbers indicate the quantified strength of the statistical association.

(left), uncertain (mid), and negative (right), of the response variables, and each answer/bar is marked by a different hatching pattern. The numbers above each set of bar graphs present the percentage distribution of the answers. Lastly, the numbers in Figure 2(b) present the strength of the statistical association, either Gamma value or Somers' D value, between the independent/explanatory variable and the response variable. The color scheme is shown in the color bar, ranging from dark blue (no association) to yellow (strong association). It was found that the respondents' age has a strong association (γ = .44) with their opinions on the concept of WTSD; their year since diagnosis (γ = .20), the awareness of WTSDs (γ = .25), the Effectiveness of their current treatment on managing tremor ($\gamma = -0.21$), the side effects of their current treatment (γ = .14), and the overall satisfaction of the treatment ($\gamma = -0.24$) have a moderate association with their opinions on the concept of WTSD; the Effectiveness of their current treatment on managing tremor has a strong association ($\gamma = -0.31$) with their opinions on trying a WTSD; the sex of the respondents (γ = .22) and overall satisfaction of the treatment ($\gamma = -0.20$) have a moderate association with their opinions on trying a WTSD; and lastly, the rest of the cross-tabulation analysis showed weak association (γ within ±.09).

Other than the strength of statistical association, it was found that the respondents' age influences their opinions on the concept of WTSDs ($p < .05$). The younger age group has more positive views on the concept of WTSD when compared to the older age group; however, such association was not found between their age and their opinions on trying a WTSD (p = .60). Similarly, their awareness of WTSDs led to a positive opinion on the concept of WTSD ($p < .05$); however, no such association was found between their awareness of WTSD and their opinions on trying a WTSD (p = .34).

In addition to the aforementioned factors, it was found that the respondents' satisfaction with the treatment they are receiving also plays a significant role in their opinions on the concept of WTSD ($p < .05$) and on trying a WTSD ($p < .05$). The respondents who are unsatisfied with their current treatments are generally more favorable to the concept of a WTSD and on trying a WTSD, while the other respondents are either uncertain or negative about this technology.

Among the four aspects of the treatments, only the Effectiveness of the treatments on managing tremor has significant associations with the respondents' opinions on WTSD ($p < .05$ for both opinions). It showed that the respondents who are experiencing ineffective treatments are generally more open to the WTSD technology, while the others who are satisfied with the Effectiveness of the treatments are generally not interested at the moment.

Lastly, year since diagnosis, sex, cost of the treatment, side effects, and difficulty of managing treatment in daily life do not significantly associate with the respondents' opinions on WTSD. The factors that statistically associate ($p < .05$) with the opinions on the WTSDs are labeled by "*" in Figure 2(a).

Design requirements and affordability. Design requirements and affordability are the other primary outcomes examined. Figure 3(a) shows the respondent-reported significance of seven design aspects of a WTSD. They are accurate motion, weight and size, cost, comfort, safety, quick response, and adaptability to lifestyle. All seven aspects were ranked in order from the lowest significance (1) to the highest significance (7). The x axis shows the stacked frequency count of the significant levels. The "Neutral" levels of all design aspects are centered at 0. The Kendall's W test on the ranking results found a high variability (77.9%, i.e., Kendall's W = .221) on the ranking, indicating that not every respondent agreed on the answers; however, the Friedman's ANOVA test rejected the null hypothesis of equal mean ranks ($p < .05$), which indicates that a statistically-significant similarity in the ranking answers was found to represent the opinion of the group. Therefore, based on the averaged quantified ratings, i.e., the lowest significance has a value of one and the highest significance has a value of seven, the most important design requirement is the adaptability to lifestyle (4.30), followed by weight and size (3.79), accurate motion (3.76), comfort (3.26), safety (2.48), quick response (1.99), and cost (1.43).

Figure 3(b) shows the maximum acceptable price range of a WTSD reported by the respondents with PD. The percentage of respondents who would spend under $100, $100–$500, $500–$1,000, $1000–$3,000, and $3000–$5000 are 11%, 54%, 24%, 9%, and 2%, respectively.

MDS Respondents

Demographics. Among the 61 identified MDS, 25 responded, and 24 completed the survey. The response rate and the completion rate are 41.0% and 39.3%. Table 4 presents the demographics regarding their years of practice, opinions on the importance of treating tremor, main approaches prescribed for parkinsonian tremor management, and opinions on using WTSDs. The year of practice ranges from 4 to 40, the average ± standard deviation (SD) is 23.0 ± 10.3. Among the MDS who completed the survey, 10 (41.7%) responded that treating tremor is very important, 10 (41.7%) rated it as moderately important, 4 (16.6%) rated it as slightly important, and no one considered treating tremor extremely important or not important. As for the prescribed approaches for managing tremor, the majority of the MDS respondents use oral medication (24, 100%) and brain surgery (20, 83.3%), 10 (41.7%) use botulinum toxin, and 3 (12.5%) use assistive devices. Lastly, 8 (33.3%) MDS have positive opinions on prescribing WTSDs for their patients vs. 2 (8.3%) considered negative. More than half of the MDS respondents' opinions (14, 58.4%) were neutral.

Knowledge and opinions on WTSD technology. Similar to the respondents with PD, the knowledge and opinions of the MDS on WTSD technology are among primary outcomes

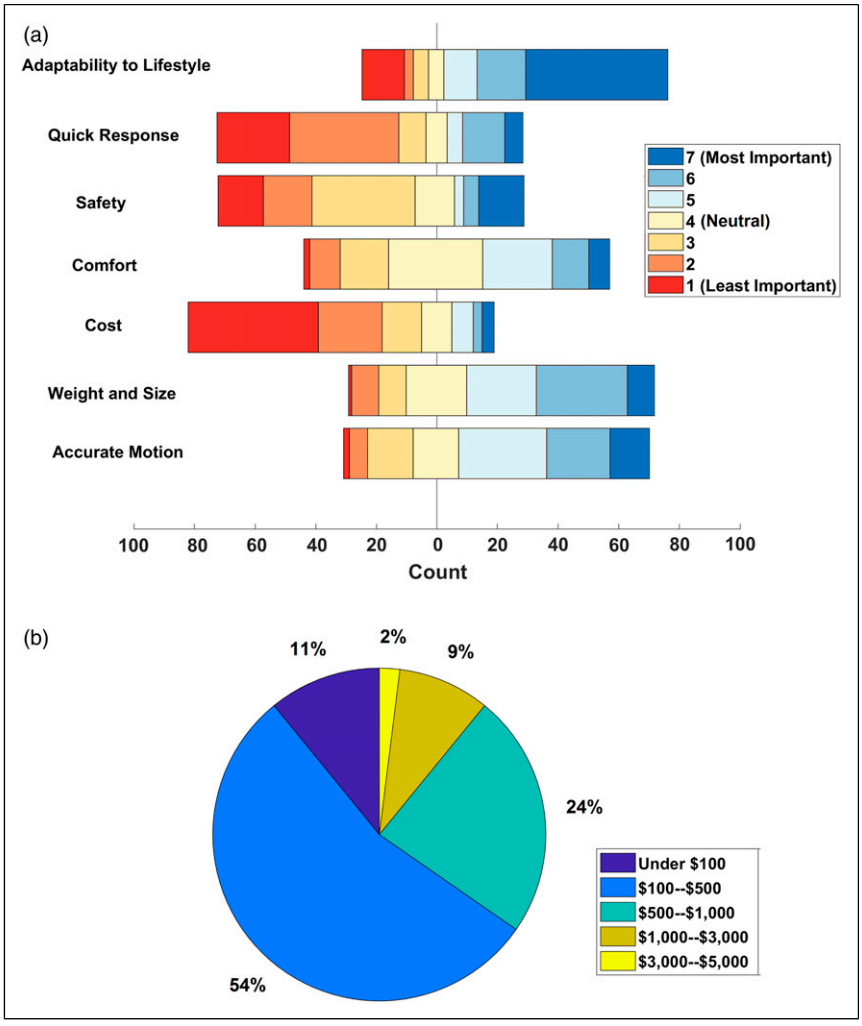

Figure 3. a. Seven design requirements ranked by the respondents with PD. b. Distribution of the acceptable price of a WTSD.

examined for the MDS respondents. It was found that most of the MDS (23, 95.8%) were aware of the existence of WTSD technology, only 1 (4.2%) reported that they were not aware of such technology. Among the MDS who are aware of WTSD technology, 1 (4.2%) has tried WTSDs on patients, 3 (12.5%) have participated in a WTSD-related research study, and 19 (79.2%) have heard of the concept. Among the 23 MDS who are aware of the WTSD technology, 4 (16.7%) obtained the knowledge from their patients, 5 (20.8%) from their co-workers, 14 (58.3%) from literature, 8 (33.3%) from news, 1 (4.2%) from industry contacts, and 1 (4.2%) from an international conference.

Based on their knowledge of WTSDs, all MDS respondents believed that WTSDs are not widely used. Among the ones who did not believe that WTSDs are widely used, 11 (45.8%) considered that the size and weight of WTSDs restricted their adoption among the end users, 12 (50%) indicated the prohibitive cost of WTSDs, 9 (37.5%) indicated the lack of ergonomic designs, 5 (20.8%) indicated that the design was too complex, 4 (16.7%) indicated that they were ineffective in managing tremor, and 22 (91.7%) indicated inadequate knowledge of the WTSDs among professionals. The distribution of each opinion is shown in Figure 4(a).

Lastly, the influence of the MDS' opinion on whether they will recommend WTSDs (when they become available in the market) to their patients and whether they will participate in WTSD-related studies is shown in Figure 4(b). The MDS' opinion on WTSD technology is the independent variable (x axis) with three categories, i.e., Positive, Neutral, and Negative; their attitude towards recommending WTSD to patients and participating in WTSD-related studies are the dependent variables, which consist of three categories, i.e., Yes (left), Uncertain (mid), and No (right). Each of these categories is marked by a different hatching pattern. The descriptive statistics are shown by the bar graphs. Strong associations were found between the MDS' opinions on WTSD technology and the two dependent variables, i.e., the MDS' opinion on whether they will recommend WTSDs

Table 4. Demographics of the movement disorder specialists.

Characteristics	MDS (N = 24), n (%)
Opinion on treating tremor	
Extremely important	0 (0%)
Very important	10 (41.7%)
Moderately important	10 (41.7%)
Slightly important	4 (16.6%)
Not important	0 (0%)
Prescribed treatments	
Oral medication	24 (100%)
Brain surgery	20 (83.3%)
Botulinum toxin	10 (41.7%)
Assistive device	3 (12.5%)
Opinion of using WTSD	
Positive	8 (33.3%)
Neutral	14 (58.4%)
Negative	2 (8.3%)
Years of practice (Mean ± SD): 23.0 ± 10.3	

(when they become available in the market) to their patients (γ = .48) and whether they will participate in WTSD-related studies (γ = .51). The numbers above each set of bar graphs present the percentage distribution of the answers.

It was found that MDS' opinion significantly influences their decisions (both $p < .05$) on the acceptance of WTSD technology. The MDS with negative opinions on the WTSD technology are more skeptical about recommending WTSDs to their patients and participating in WTSD-related studies, while the MDS with positive opinions on the WTSD technology are more willing to accept the technology.

Design requirements. In addition to the knowledge and the opinions of the MDS regarding WTSD technology, the design requirements of a WTSD were the other primary outcomes examined for the MDS respondents. Figure 5 shows the MDS-reported significance of seven design aspects of a WTSD. They are the same as the ones presented to the respondents with PD. The Friedman's ANOVA test found no significant difference (p = .645) between the obtained rankings from the MDS and the equal mean ranks. The Kendall's W test on the ranking results showed a 97.1% (Kendall's W = 0.029) variability. Although no agreement on the rank of the seven design aspects of a WTSD was obtained, the following ranking is presented herein as a descriptive result without statistical significance. Based on the average ratings, the safety has the highest importance (4.50), followed by accurate motion (4.33), quick response (4.29), adaptability to lifestyle (3.92), weight and size (3.67), comfort (3.71), and cost (3.58).

Discussion

This study is part of a larger project that aims to develop a user-centered WTSD for individuals whose tremors are not effectively managed by traditional treatments. Although many WTSDs have already been developed, none of them have become commercially available and used by people living with parkinsonian tremor. This study aimed to understand better the stakeholders' opinions on WTSD technology and their requirements for such a device. Findings from this study will provide essential guidance for developing future WTSDs that are more acceptable by the end users, and facilitate the transition of WTSDs from the lab to end users.

Current state and opinions on traditional treatments and WTSDs

The demographics of the individuals with PD have shown that the majority of the respondents received medication to manage their tremor. A small group received other treatments, i.e., DBS and exercise; however, none of them have been using a WTSD to manage their tremor. This finding supports the hypothesis that the technology of tremor suppression devices has not been developed to the level that it can be accepted by the end users. In addition, this hypothesis is also supported by the responses from the MDS; namely, that the main treatments that they have been prescribing to the patients are medication and brain surgery (Table 4).

As one of the nine factors, age has shown a strong association with the opinion of parkinsonian participants on WTSDs. It was found that older participants are generally not optimistic about this technology. Although the reasons for this result were not explicit in the current study, it is essential to identify these factors in a follow-up study so that future WTSDs can be designed to be more inclusive for end users from different age groups.

The technology of WTSD has been developed for a couple of decades; however, most of the WTSDs are still being evaluated in the lab. The drawbacks of the existing WTSDs have certainly played a role in restricting their acceptance by the end users; however, a major finding was identified in this survey that more than half of the respondents with PD (52.5%, Table 3) were not aware of any WTSDs. Due to this unawareness, the end users may not have used or inquired about such technology. In addition, meaningful engagement between the researchers and the end users may not have been established due to the unawareness of any WTSDs, leading to the aspects of a WTSD that the end users value the most not being properly considered in the design process. Furthermore, it was found that only 2% (Table 3) of the respondents with PD have heard the concept of WTSDs from their primary doctors; however, this does not indicate that their primary doctors are not aware of the technology. In fact, most of the MDS respondents (95.8%) know of the existence of the technology, and 16.7% have tried a WTSD or participated in a related

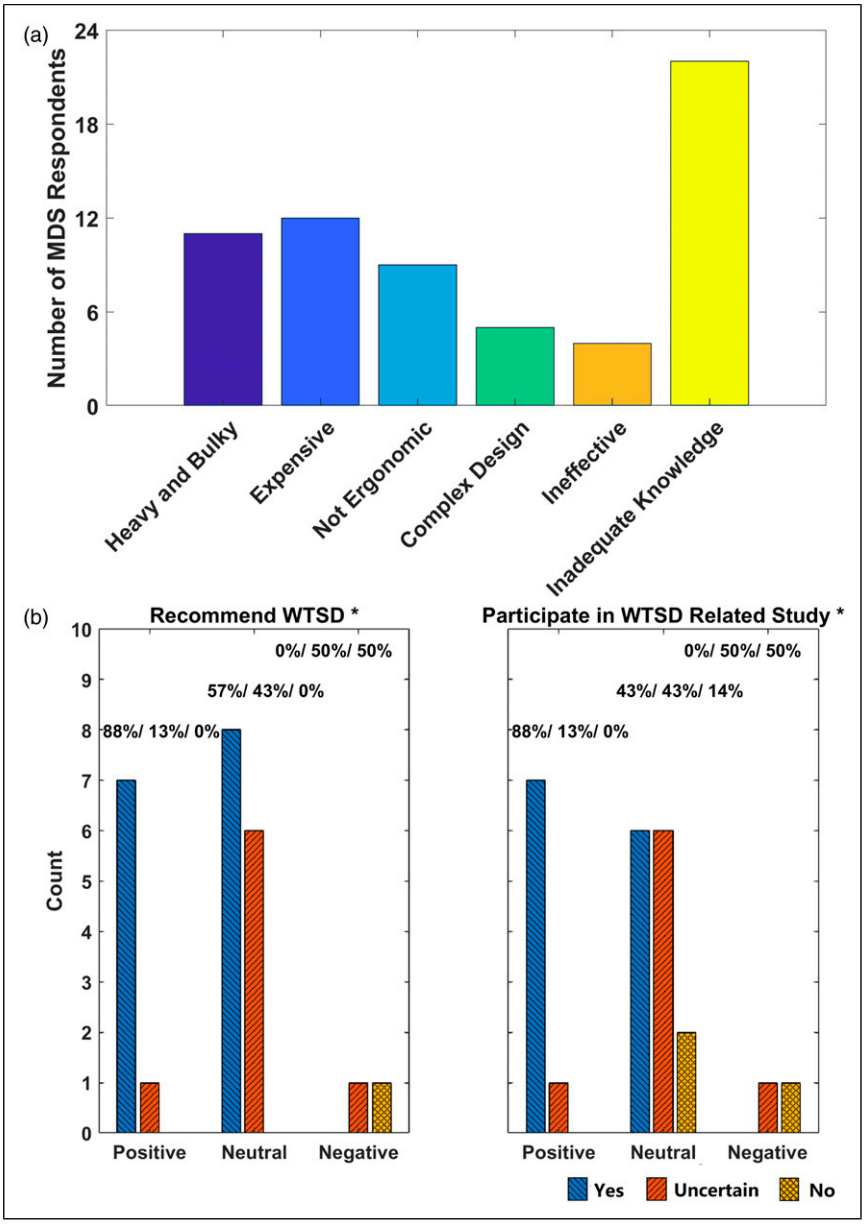

Figure 4. a. MDS rated drawbacks of the current WTSDs that have restricted the acceptance by end users. b. The influence of the MDS' opinion on whether they will recommend WTSDs to their patients (left) and whether they will participate in WTSD-related studies (right). The *y* axis of each bar graph shows the frequency count, and the *x* axis shows the options of each independent/explanatory variable, i.e., Positive, Neutral, and Negative. The numbers above each set of bar graphs present the percentage distribution of the answers. Statistically-significant associations ($p < .05$) are labeled by "*".

research study. Although the MDS are aware of the technology, most of them (91.7%, Figure 4(a)) believe that there is not enough knowledge of the WTSDs among the professionals, which may explain their unwillingness to inform their patients about this technology.

Although there is a lack of knowledge about WTSD technology among the stakeholders, the survey found that most of the end users (68.3%, Table 3) have positive opinions on the concept of WTSDs. In addition, the cross-tabulation analysis showed that people who are aware of the technology have more positive opinions than those who are not aware. This indicates that higher exposure of the technology to the end users likely will facilitate its acceptance. Interestingly, no statistical association was identified between the awareness of the technology and end users' opinion on trying a WTSD. This is likely because only a small group of individuals (3%, Table 3) had the experience of using a WTSD. This finding also aligns with

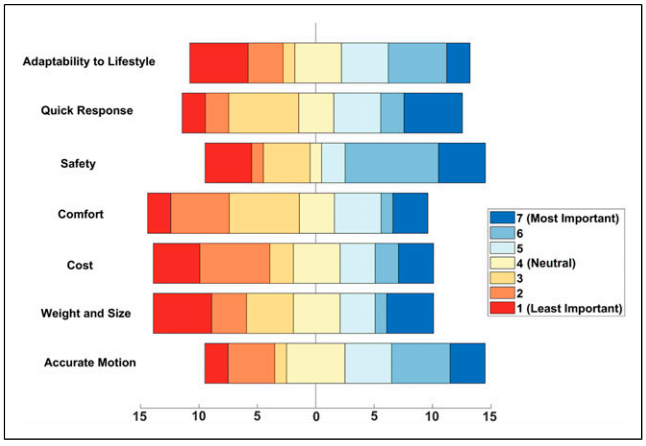

Figure 5. Seven design requirements ranked by the movement disorder specialists respondents.

the current state of development of WTSDs in the literature, in which only a few WTSDs[45] have been preliminarily tested on a small group of people in the world.

In addition to the awareness of the technology, the cross-tabulation analysis found a statistically-significant association between the end users' experience on their current treatment and their opinions on the concept of WTSD and opinion on trying a WTSD. The end users show more enthusiasm towards the WTSD, as an alternative treatment approach, when they have experienced difficulties with their current treatments. However, not every surveyed aspect of the received treatment contributed equally to this outcome. It was found that, among the four surveyed aspects, only the Effectiveness of the treatments showed a significant association with the end users' opinions on the WTSD, and the rest presented only weak associations. Therefore, it is sufficient to conclude that the low Effectiveness of the current treatments is the leading factor that encourages the end users to find alternative treatments.

All MDS participants have confirmed that it is important to treat tremor. The level of treatment certainly varies by the severity of each individual's tremor; however, the reported MDS' opinion on treating tremor may provide some indirect evidence regarding the ineffectiveness of the current treatment for managing tremor. The ineffectiveness of the current treatments for managing tremor and the awareness of the WTSDs have encouraged the end users to accept WTSDs; however, the opinions of the MDS on WTSDs also played a crucial role in the acceptance of this technology. It was found that the MDS who do not have a positive opinion on WTSDs are more skeptical about recommending the technology to their patients. Therefore, getting more MDS involved in developing and evaluating WTSDs may provide them with a better understanding of the technology, hence encouraging them to recommend the technology to their patients.

Both individuals with PD and health professionals certainly are essential stakeholders in determining the acceptance of WTSD technology; however, the family caregivers, especially those supporting the elderly with PD, also play an essential role in adoption. Therefore, other than their opinions on this technology and desired functionality, the social impact of this technology on the caregivers' life, such as employment, mental health, and family relationship, should be investigated. The current study has surveyed both MDS and individuals with PD; however, a comprehensive follow-up study that includes caregivers should be carried out.

In this study, several aspects related to the PD treatments were found to play significant roles in the parkinsonian participants' opinions on WTSDs; however, an interesting aspect of PD treatments that was not studied is the doses of daily medication taken. This factor could provide further insights into the participants' opinions on WTSDs, which should be addressed in a follow-up study.

Design requirements and constraints for future WTSDs

The ultimate goal of WTSDs is to provide an alternative tremor management approach to individuals living with tremor. In order to promote the acceptance of WTSDs by end users, it is essential to understand which aspects they value the most. The survey showed that the three most important aspects are the adaptability to lifestyle, the weight and size of a WTSD, and accurate motion. From the design perspective, future WTSDs should include the following features:

1. Mechanism that allows easy donning and doffing process.
2. Unobtrusive and compact hardware design that does not hinder upper-limb motion.
3. Distributed actuation and transmission system that is remotely located from the hand.
4. Light weight. Note that the maximum acceptable weight was not surveyed as part of this study. A recent study assessed a WTSD on an individual with PD reported that a weight of 580 g is acceptable.[13]
5. An optimal control system that considers the dynamic model of the WTSD for accurate motion control.

In addition to the aforementioned aspects, it was surprising to find that safety was ranked in the lower half of importance by the respondents with PD. A potential reason could be the daily struggle with tremor has eroded the participants' patience with the treatments that they are undergoing. Furthermore, as a disease with no cure, individuals with PD take action by involving themselves in more fundamental research initiatives. As a group, it is

likely that they are more open to alternatives as it is an understood community effort to support finding new treatments. Hence, the strong demand for an alternative approach may outweigh the importance of safety. However, this does not suggest that safety should be considered as a lower priority than any other aspects. To ensure the safety of a WTSD, both software and hardware measures should be implemented in the design process of a WTSD; in addition, an emergency stop button should also be incorporated.

Unlike the ranking results from the end users, the MDS respondents considered that the safety of a WTSD is the most important aspect, followed by accurate motion and quick response. Noticeably, the MDS were more concerned about the functionality and safety aspects of a WTSD than its cost and ergonomic design, while the end users expressed the opposite. However, considering that no agreement was achieved among the MDS in this question, more MDS respondents are required in order to draw a robust conclusion about their opinions on the design requirements of a WTSD.

Limitations

Since there is no nationwide database of individuals with PD in Canada, the online questionnaire was first sent to the Parkinson's associations and support groups in each province, which may have introduced a selection bias by the third party. In addition, the spread of COVID-19 has significantly impacted the recruitment process as most in-person activities have been canceled. This unfortunate situation has prolonged the time necessary to receive a proper number of respondents for data analysis.

Because of the inherent nature of the online survey, a self-selection bias may play a role in the obtained results. People who already know about the technology may be more likely to participate in the survey, and to be in favor of adopting the WTSD technology. In addition, people without regular access to the Internet, or who are not proficient with using a computer or a tablet, may not have had access to this survey. Future work is needed to collect the perceptions from this group of people. Lastly, whether individuals live at home or in an institution may also play a critical role in determining the functionality and acceptability of the WTSDs, which should be investigated in the future study. To facilitate the aforementioned follow-up studies and to investigate the issue of user acceptability more broadly and comprehensively, the "Matching Person and Technology" model[46] can be used.

The design requirements section asked the respondents to rank the importance of seven aspects of their imaginary WTSD. Since there were no conceptual graphics provided with this question, the answers obtained may be limited by the respondent's imagination or their impressions of other types of wearable devices.

In addition, several questions developed in this survey used Likert scales with a limited number of points, which may not provide enough resolution to the answers.

Conclusions

This study has highlighted the current state of parkinsonian tremor management in Canada. The results have given insights into the opinions of individuals with PD and MDS on tremor management approaches and WTSDs. Furthermore, this study has gathered information on the desired design requirements of future WTSDs from the stakeholders.

Both groups of participants are generally open to the idea of using WTSDs for managing tremor; however, many respondents require more evidence of the successful implementation of WTSDs. This suggests that extensive clinical evaluations of the WTSDs should be conducted in order for them to be accepted by stakeholders; note that very few of the existing WTSDs have been tested on humans. The information on the design requirements can be used as a guideline for the development of future WTSDs and optimization of the existing WTSDs, such that future versions could potentially become available for end users to use in daily life.

Appendix

Questionnaire for Individuals with PD

1. Please specify your age: ***Under 30; 30–3 years old; 40–49 years old; 50–59 years old; 60–69 years old; 70–79 years old; Above 80 years old***.
2. Please specify your sex: ***Female; Male***.
3. Please specify how long you have been diagnosed with Parkinson's disease (if less than 1 year, please write 1).
4. What treatment(s) are you currently using to manage upper limb tremors? Please select all that apply: ***Brain surgery; Medication (including botulinum toxin); Wearable tremor suppression device; No treatment; Other***.
5. Select the keywords that best describe the treatment you are currently receiving to suppress tremors. Please select all that apply: ***Efficient; Inefficient; Affordable; Expensive; Comes with side effects; No obvious side effects; Easy to manage in daily life; Hard to manage in daily life, Other***.
6. If you take medication to supress tremors, please select all obstacles/difficulties you have encountered with it. Please select all that apply: ***Drug is not effective for tremor; Effect of Drug wears off quickly; Side effects; Forget to take the pills; Other***.
7. If you have undergone brain surgery to supress your tremors, please list all obstacles/difficulties you have encountered with it. Please select all that apply: ***Complications due to surgery; Symptoms are not improved as expected; Did not have surgery; Other***.

8. Do you think the range of motion of your hand is limited by Parkinson's disease: ***Yes; No; I don't know***.
9. Has your doctor ever provided you with information on wearable tremor suppression devices: ***Yes; No***.
10. Please grade your knowledge on the current tremor management approaches, i.e., medication, deep brain stimulation, wearable tremor suppression device, from one of the five options: ***Actively participating in related research study; Have studied related literature; Read about related news/articles; Heard of the concept; Not aware of it***.
11. Please rank/reorder the following tremor suppression methods in order of preference (3 being the top pick, 1 being the least): ***Brain surgery; Medication; Wearable tremor suppression device***.
12. Have you ever participated in a research study related to the development of wearable tremor suppression devices: ***Yes; No***.
13. If you are using/have used a device in the past that suppressed tremors are there any reasons why you are/were unsatisfied with it? Please select all that apply: ***Inaccurate motion; Heavy and bulky; Expensive; Not comfortable; Safety concerns; Slow response to your movements; Insufficient working hours; Never used; Other***.
14. Please select how you feel about a wearable tremor suppression device being designed to suppress parkinsonian tremors: ***Excellent idea; Good idea; Uncertain; I don't think it would be an improvement over current treatment; Other***.
15. If you are currently using a treatment for tremor suppression, please select how strongly you feel in favor of trying a wearable tremor suppression device: ***Very strongly; Fairly strongly; Would have to see the design; Not interested; I am happy with my current treatment; Other***.
16. Please rank/reorder the following seven aspects that you think are important for the design of a wearable tremor suppression device (7-most important, 1-least important): ***Accurate motion; Lightweight and compact; Lightweight and compact; Comfortable design; Safety; Fast response to movements; Easily adaptable to lifestyle (does not get in the way of daily activities)***.
17. If you would like to use a wearable tremor suppression device, what would be the maximum acceptable price range for you: ***Under $100; $100–$500; $500–$1000; $1000–$3000; $3000–$5000; Above $5000***.

Questionnaire for the MDS

1. Please indicate how many years you have treated patients with Parkinson's disease. (if less than 1 year, please write 1).
2. Please select the main approach(es) you are currently prescribing to manage Parkinson's disease and tremor? Please select all that apply: ***Brain surgery; Oral medication; Botulinum toxin; Wearable tremor suppression device; Other***.
3. From the list below, please rank/reorder the tremor management methods in order of which you think is the most used in your field (7 being used the most): ***Brain surgery; Oral medication; Botulinum toxin; Wearable tremor suppression device; Other***.
4. Please select how important you believe treating tremor is in comparison to other symptoms of Parkinson's disease: ***Extremely important; Very important; Moderately important; Slightly important; Not at all important***.
5. Please choose what you think are the difficulties with treating/managing tremors with medications. Please select all that apply: ***Lack of effectiveness of medication; Effect of medication wears off; Side effects; Other***.
6. What is your opinion of patients using wearable tremor suppression devices: ***Positive; Neutral; Negative***.
7. Please select your level of knowledge of wearable tremor suppression devices: ***Tried such a device with patients; Participated in research study; Heard of the concept; Never heard of it; Other***.
8. If you have heard about wearable tremor suppression devices, where or how did you hear about them? Please select all that apply: ***Patient; Co-worker/Research collaborator; Literature review; News; Industry contact; Other***.
9. Do you think wearable tremor suppression devices are being widely used to suppress tremors: ***Yes; No***.

9.1 If you answered "No" to the question above, why do you think so? Please select all that apply: ***Heavy and bulky; Expensive; Not ergonomic; Complex design; Ineffective; Inadequate knowledge of the devices among professionals; Other***.

10. Please list any wearable tremor suppression devices that you know of that are being successfully used in this field, if known.
11. Please rank/reorder the following seven aspects according to their level of importance in the design of a wearable tremor suppression device (1-least important, 7-most important), please select one score for each option: ***Accurate motion; Lightweight and compact; Inexpensive; Ergonomic design; Safety; Fast response to user commands; Easily adaptable to lifestyle (Does not impair daily activities)***.
12. Would you be willing to recommend wearable tremor suppression devices to your patients if they became available: ***Yes; No; Not sure***.
13. Would you be interested in participating in a research study related to the development of wearable tremor suppression devices: ***Yes; No; Not sure***.

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Author contributions

YZ researched literature, YZ, KGH, MEJ, SJG, MDN, and ALT conceived the study. YZ, MEJ, MDN, and ALT contributed to protocol development, and obtained research ethic approval. YZ and DB recruited MDS and participants with PD. YZ, SJG, MEJ, MDN, and ALT interpreted the data. YZ processed and analyzed the data and wrote the manuscript. All authors reviewed, edited, and approved the manuscript.

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