Tremor Irregularity, Torque Steadiness and Rate of Force Development in Parkinson’s Disease

Martin H. Rose, Annemette Løkkegaard, Stig Sonne-Holm, and Bente R. Jensen

We investigated lower-extremity isometric tremor Approximate Entropy (irregularity), torque steadiness and rate of force development (RFD) and their associations to muscle activation strategy during isometric knee extensions in patients with Parkinson’s disease (PD). Thirteen male patients with idiopathic PD and 15 neurologically healthy matched controls performed isometric maximal contractions (extension/flexion) as well as steady submaximal and powerful isometric knee extensions. The patients with PD showed decreased isometric tremor irregularity. Torque steadiness was reduced in PD and the patients had increased muscle coactivation. A markedly lower RFD was found in PD and the decreased RFD correlated with reduced agonist muscle activation. Furthermore, patient RFD correlated with the Movement-Disorder-Society-Unified-Parkinson’s-Disease-Rating-Scale 3 (motor part) scores. We concluded that both knee isometric tremor Approximate Entropy and torque steadiness clearly differentiate between patients with PD and healthy controls. Furthermore, severely compromised RFD was found in patients with PD and was associated with decreased agonist muscle activation.

Keywords: Parkinson’s disease; rate of force development; ApEn; steadiness; muscle activation

Introduction

Parkinson’s disease (PD) is a neuro-degenerative progressive disease characterized by the cardinal symptoms: bradykinesia, rigidity, tremor and postural instability. Progression of the disease leads to a challenged motor function with changes in balance and ambulation. The essential pathophysiology of PD is the degeneration of dopaminergic cells within substantia nigra and the subsequent dopamine depletion of the striatum (Bernheimer, Birkmayer, Hornykiewicz, Jellinger, & Seitelberger, 1973). Abnormal oscillating neural activity within the basal ganglia circuits is
related to bradykinesia and tremor (Bergman & Deuschl, 2002; Berardelli, Rothwell, Thompson, & Hallett, 2001). Tremor is defined as a rhythmical, involuntary oscillatory movement of a body part (Deuschl, Bain, & Brin, 1998) and tremor analysis can be used as a noninvasive approach to gain information of dominant pathological CNS oscillators (Bergman et al., 2002; McAuley & Marsden, 2000). Approximate Entropy (Pincus, 1991) (ApEn), a metric quantifying tremor irregularity, may have this potential in the case of PD. Indeed changes in ApEn toward normal values (increased irregularity) have been reported after treatment modifying basal ganglia neural circuits (ablation or Deep Brain Stimulation) in PD, when calculated from resting and postural tremor (Kovacs, Balas, Illes, Kellenyi, Doczi, Czopf, Poto & Nagy, 2006; Sturman, Vaillancourt, Metman, Bakay, & Corcos, 2004). An optimized use of the ApEn algorithm based on an isometric force time-series has been suggested to increase the biological sensitivity of this metric (Rose, Bandholm, & Jensen, 2009). Isometric tremor is defined as tremor occurring as a result of muscle contraction against a rigid stationary object (Deuschl, Bain, & Brin, 1998) and has the advantage over resting and postural tremor of reduced contribution from mechanical-reflex oscillators and thereby focusing the analysis on CNS properties. Thus, isometric tremor ApEn could provide quantitative information of PD in the evaluation of interventions as e.g., physical rehabilitation regimes, which are expected to induce a less dramatic effect on neural circuits compared with neurosurgery. However, before applying this measure to an intervention study, a cross sectional evaluation has to be made.

Torque steadiness, which refers to the ability to perform muscle contractions with minimum fluctuations in torque while matching a given torque level (Enoka, Christou, Hunter, Kornatz, Semmler, Taylor & Tracy, 2003; Bandholm, Rose, Sonne-Holm, & Jensen, 2008) is another metric that could provide information of motor control in patients with PD. Torque steadiness is typically quantified in absolute terms as the standard deviation or relative as the coefficient of torque variation. Less variability implies better torque control. Different CNS pathologies including PD off medication (Oliveira, Rodrigues, Caballero, Petersen, & Shim, 2008), PD on medication (Vaillancourt, Slifkin, & Newell, 2001a), cerebral palsy (Bandholm, Rose, Slok, Sonne-Holm, & Jensen, 2009) and chronic stroke (Lodha, Naik, Coombes, & Cauraugh, 2010) are known to decrease torque steadiness (reduce performance). In PD, torque steadiness has typically been investigated involving hand and finger muscles, which in a healthy population has been associated with manual dexterity (Marmon, Pascoe, Schwartz, & Enoka, 2011). Motor control of the lower extremity is likewise essential for patients with PD as it relates to movement tasks such as arising from a chair, postural stability and walking. Indeed, decreased knee extension torque steadiness has been found in older adults with a history of falling compared with nonfallers (Carville, Perry, Rutherford, Smith, & Newham, 2007). Thus, knee-joint torque steadiness could be a quantitative performance measure related to PD and patients’ ambulation ability. Furthermore, agonist EMG during torque steadiness is shown to correlate with UPDRS motor scores (Robichaud, Pfann, Vaillancourt, Comella & Corcos, 2005) and it is likely that additional knowledge of the muscle activation strategy during torque steadiness can be obtained from the EMG signal.

In addition, when sudden changes in muscle force are required during ambulation (e.g., sit to stand transitions or restoration of postural stability after stumbling), the short action time may not allow maximal muscle force to be reached. Therefore,
the ability to exert a rapid rise in muscle force (rate of force development [RFD]) becomes highly important, as it allows reaching a high level of muscle force in the early phase of the muscle contraction. An association between decreased isometric knee extension and hip abductor RFD and postural stability has been shown in the elderly population (Chang, Mercer, Giuliani, & Sloane, 2005; Izquierdo, Aguado, Gonzalez, Lopez, & Hakkinen, 1999). Only few studies have investigated knee extension RFD in PD (Paasuke, Ereline, Gapeyeva, Joost, Mottus & Taba, 2004) and the association to the underlying muscle activation during a lower-limb RFD task is so far unresolved in PD. Likewise knowledge regarding the potential association to motor-related disease severity is lacking.

The aim of this study was to evaluate isometric tremor ApEn, torque steadiness and rate of force development and their associations to muscle activation strategy during isometric knee extensions in patients with PD.

Methods

Participants

A total of 28 men, 13 patients with idiopathic PD (age 63 ± 6 years (mean ± SD), Body Mass Index 25 ± 4, Hoehn and Yahr range 2–3, MDS-UPDRS (Goetz, Tilley, Shaftman, Stebbins, Fahn, Martinez-Martin, Poewe, Sampaio, Stern, Dodel, Dubois, Holloway, Jankovic, Kulisevsky, Lang, Lees, Leurgans, LeWitt, Nyenhuis, Olanow, Rascol, Schrag, Teresi, van Hilten & LaPelle, 2008) range 18–83) and 15 neurologically healthy age matched controls (age 65 ± 6 years, BMI 28 ± 3) were included. The patients were included from a movement disorder clinic by a movement disorder specialist. The medication was noted, and the levo-dopa equivalent dosage calculated (Tomlinson, Stowe, Patel, Rick, Gray & Clarke, 2010). As we intended to study differences between control subjects and the patients’ daily level of motor control, the patients followed their normal schedule for medication in this study; see Table 1 for clinical details. Both muscle strength, RFD and the associated EMG are influenced by antiparkinsonian medication (Corcos, Chen, Quinn, McAuley & Rotwell, 1996). The exclusion criteria for the patient group were any known diseases other than PD that might interfere with motor function. The control subjects were recruited by advertisement in a first-come, first-served fashion. The study was conducted according to the principles expressed in the Declaration of Helsinki. The Committee on Ethics in Science in Copenhagen approved the study H-3–2010–051.

Apparatus

A biomechanical examination was performed. Knee joint torque was measured with a force transducer mounted in a height adjustable ankle strap placed perpendicular to the tibia, just proximal to the medial malleolus. The moment arm was measured from the center of the ankle strap to the center of the knee joint. After standard skin preparation, bipolar surface EMG electrodes (Ambu Neuroline 720, Ballerup, Denmark) were placed over the muscle belly of the knee extensor muscles (m. vastus lateralis, m. rectus femoris and m. vastus medialis) and flexor muscles (m. biceps femoris and m. semitendinosus) according to Perotto et al. (Perotto A, Delagi EF, Lazetti J, & Morrison D, 2005). The electrodes were positioned with an
<table>
<thead>
<tr>
<th>Patient</th>
<th>Age (years)</th>
<th>Disease Duration (y)</th>
<th>BMI (Kg/m²)</th>
<th>H&amp;Y (score)</th>
<th>MDS-UPDRS (motor part)</th>
<th>MDS-UPDRS (tremor)</th>
<th>MDS-UPDRS (total)</th>
<th>Medication (LED in mg)</th>
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BMI, Body Mass Index; H&Y, Hoehn and Yahr; MDS-UPDRS, Movement Disorder Society Unified Parkinson’s Disease Rating Scale; tremor, MDS-UPDRS 315–318; LED, L-dopa equivalent dose.
inter electrode distance of 2 cm (center to center), connected to preamplifiers (×25) and further to a main EMG unit (Logger technology, 10–400 Hz, Sweden). Force and EMG signals were AD-converted (16 bit, DT 9834, Data Translation, Marlboro, Massachusetts, USA) at 1 kHz and stored on a computer for off-line analysis.

**Data Collection Procedures**

The patients were clinically examined, using the MDS-UPDRS in an interview based manner, on average two days before the biomechanical examination. Just before the biomechanical examination, the control subjects filled out the Short-Form-36 questionnaire and all participants (PD and controls) were asked about their level of physical activity. The level of physical activity was defined as: number of days per week exceeding 30 min of physical activity. Physical activity included: walking, running, biking, stair climbing, sports, rhythmic movement, gardening, etc.

The experimental part of the study was conducted in a biomechanical laboratory shielded from electromagnetic radiation. The subjects were seated in a custom-made rigid chair and to prevent accessory trunk movement the hip and shoulder were firmly strapped and both hands were placed on the thighs. Hip and knee joint angels were standardized to 95 and 100°, respectively. On-line visual force feedback was provided on a computer screen placed 1 m away at eye level. All tests were performed unilaterally and both legs were examined in a randomized order, completing one leg before assessment of the other. Exerted force and EMG were measured. All tests were performed with the patients in a self-reported “ON” state.

The subjects completed three different types of isometric muscle contractions: **Maximal muscle contractions**, **Steady submaximal muscle contractions** and **Powerful submaximal muscle contractions**. To avoid fatigue, each single test was separated by sufficient pauses, and careful verbal instructions followed by a familiarization session were given before all tests.

**Maximal Muscle Contractions.** Maximal voluntary isometric extensor and flexor knee-joint torques (MVC) were performed under supervision of an experienced exercise physiologist and special attention was made to insure that a “true” maximal force was exerted. Subjects were instructed to contract as forcefully as possible with a gradual increase in force, and to reach maximum within 2–3 s. All tests were provided with strong verbal encouragement and on-line visual force feedback. A standard of three contractions were performed for each torque direction, always performing knee extension first. If the last MVC was the highest, an extra contraction was performed.

**Steady Submaximal Muscle Contractions.** Using the on-line visual force feedback, subjects were instructed to align their exerted isometric knee extension force with a line representing 15% of their isometric MVC. The task was to maintain the force as steady as possible. After familiarization, four contractions, each lasting 25 s and separated by 65 s pauses were performed.

**Powerful Submaximal Muscle Contractions.** Subjects were instructed to “kick” (isometric) their on-line force above a line representing 50% MVC as fast as possible (RFD task). After verbal initiation of the trial, the start cue was given as a visual stimulus on the computer screen. The visual stimulus arrived randomly between 1–10 s after the verbal initiation of the trial. Five contractions were performed.
Data Analysis

Maximal Muscle Contractions. Initially force data were averaged in to 100 ms blocks. EMG data were moving root mean square (RMS) filtered (window size 100 ms, step length 100 ms), resulting in 100 ms RMS EMG values. Secondly, moving average (window size 1 s, step length 100 ms) was calculated and MVC for each force direction and maximal EMG for each muscle was selected as the highest 1-s value among all contractions. Hamstring-quadriceps force ratio was calculated as maximal flexion MVC/maximal extension MVC.

Steady Submaximal Muscle Contractions. Initiation and cessation data were removed and the remaining 20 s period was analyzed. For the isometric tremor ApEn calculations data were 3–30 Hz digital bandpass filtered (100 point FIR filter, Hamming window) and subsequently down-sampled to 30 Hz as recommended (Rose et al., 2009). The ApEn embedding dimension was set to 2 and the time domain noise limit was set to 0.001 V, corresponding to the level of nonbiological noise (approximately 0.1*SD of the force time-series). For details regarding the calculation of ApEn, please see Pincus, 1991 and Rose et al., 2009. In addition frequency analysis was used to quantify power in the 3–6 and 8–12 Hz tremor bands relative to total power (0–30 Hz). Coefficient of variation (CV = SD/mean) was calculated as a measure of torque steadiness.

EMG was moving root mean square filtered (window size 21 ms, step length 1 ms) and normalized to max EMG. Each RMS EMG value for each muscle was weighted with the relative proportion of the total physiological cross-sectional area as reported in the literature (Wickiewicz, Roy, Powell, & Edgerton, 1983). The overall extensor muscle activation was then calculated by summing the RMS EMG for the extensor muscles. The relative proportions of 0.47, 0.20 and 0.33 were used for m. vastus lateralis, m. rectus femoris and m. vastus medialis, respectively. Likewise, the overall flexor muscle activation was calculated using the relative proportions of 0.25 and 0.75 for m. semitendinosus and m. biceps femoris, respectively. During the performed knee extensions, agonistic and antagonistic muscle activation corresponded to the extensor and flexor muscle activation, respectively. Instantaneous muscle coactivation was calculated as (agonist muscle activation/antagonist muscle activation)*100 for each RMS EMG observation. Coactivation for each contraction was calculated as the average of the instantaneous coactivation values and the reported coactivation values are mean of four contractions.

Powerful Submaximal Muscle Contractions. The exerted force was normalized to MVC. EMG was processed as described for the Steady submaximal muscle contractions. The absolute rate of force development (RFD = Δtorque/Δtime), relative RFD (Δ%MVC/Δtime), mean agonist and antagonist muscle activation, as well as mean muscle coactivation were calculated for the time-period corresponding to 10–35% MVC. In addition, premotor reaction time (time from visual trigger to onset of raw agonist EMG [exceeding baseline mean ± 4*SD]), electromechanical delay (time from onset of raw agonist EMG to onset of muscle force [exceeding baseline mean ± 4*SD]) and reaction time (premotor reaction time + electromechanical delay) were calculated. Data from the three contractions with the highest RFD values were selected for analyses and average values are reported.

All data were analyzed off-line using MATLAB version 2006b (Mathworks, Inc., Natick, Massachusetts, USA).
Statistical Analysis

No significant intraindividual leg differences (most affected vs. less affected) were observed for the majority of the effect parameters. Therefore mean values of both legs were used. A general linear model (MINITAB Inc., State College, Pennsylvania, USA) was used to compare groups on effect parameters and age was included in the models as a covariate. Model residuals were normally distributed and variance homogeneous. Pearson’s correlation analysis was used to determine potential associations between RFD, isometric tremor ApEn or torque steadiness values and MDS-UPDRS 3 (motor part). Multiple regression backward elimination analysis, including agonist muscle activation, antagonist muscle activation, extension MVC and the ApEn values, was used to determine main predictors of absolute RFD. The Mann-Whitney Test was used to compare the level of physical activity. Values of \( P \) less than 0.05 were considered statistically significant. Bonferroni corrections were performed when familiar hypotheses were tested (marked in Table 2).

Table 2  Neuromechanical Properties

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (± 1 SD)</th>
<th>Parkinson’s</th>
<th>Controls</th>
<th>Statistics</th>
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<tbody>
<tr>
<td><strong>Maximal muscle contractions</strong></td>
<td></td>
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<tr>
<td>(a) Extension MVC (Nm)</td>
<td>209.4 ± 58.6</td>
<td>229.8 ± 57.0</td>
<td>( P = .185 )</td>
<td></td>
</tr>
<tr>
<td>(a) Flexion MVC (Nm)</td>
<td>91.16 ± 30.7</td>
<td>92.59 ± 22.4</td>
<td>( P = .494 )</td>
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<tr>
<td>(a) Hamstring Quadriceps Ratio</td>
<td>0.445 ± 0.12</td>
<td>0.418 ± 0.11</td>
<td>( P = .527 )</td>
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<tr>
<td><strong>Steady muscle contractions</strong></td>
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<tr>
<td>(b) Torque steadiness (% of mean)</td>
<td>2.020 ± 0.91</td>
<td>1.473 ± 0.36</td>
<td>( P = .020^* )</td>
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<tr>
<td>(c) Isometric tremor ApEn (nats)</td>
<td>1.075 ± 0.08</td>
<td>0.947 ± 0.15</td>
<td>( P = .009^* )</td>
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<tr>
<td>(d) Coactivation (% of agonist EMG)</td>
<td>38.38 ± 28.5</td>
<td>15.47 ± 7.11</td>
<td>( P = .002^* )</td>
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<tr>
<td>(e) 3–6 Hz band (% total power)</td>
<td>69.19 ± 13.5</td>
<td>70.03 ± 10.8</td>
<td>( P = .856 )</td>
<td></td>
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<tr>
<td>(e) 8–12 Hz band (% of total power)</td>
<td>13.36 ± 9.44</td>
<td>11.46 ± 5.85</td>
<td>( P = .520 )</td>
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<tr>
<td><strong>Powerful muscle contractions</strong></td>
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<tr>
<td>(f) Absolute RFD (Nm/s)</td>
<td>935.4 ± 715</td>
<td>1739 ± 470</td>
<td>( P = .001^* )</td>
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<tr>
<td>(f) Relative RFD (% MVC/s)</td>
<td>411.6 ± 251</td>
<td>764.8 ± 190</td>
<td>( P &lt; .001^* )</td>
<td></td>
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<tr>
<td>(h) Coactivation (% of agonist EMG)</td>
<td>38.14 ± 22.7</td>
<td>19.28 ± 10.6</td>
<td>( P = .002^* )</td>
<td></td>
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<tr>
<td>(h) Agonist activation (% max EMG)</td>
<td>62.80 ± 20.8</td>
<td>95.10 ± 35.9</td>
<td>( P = .008^* )</td>
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<tr>
<td>(h) Antagonist activation (% max EMG)</td>
<td>22.09 ± 11.7</td>
<td>17.09 ± 7.49</td>
<td>( P = .195 )</td>
<td></td>
</tr>
<tr>
<td>(i) Electro mechanical delay (ms)</td>
<td>37.70 ± 6.64</td>
<td>34.81 ± 5.86</td>
<td>( P = .232 )</td>
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</tr>
<tr>
<td>(j) Premotor reaction time (ms)</td>
<td>279.8 ± 30.2</td>
<td>277.4 ± 26.1</td>
<td>( P = .820 )</td>
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<tr>
<td>(j) Reaction time (ms)</td>
<td>317.5 ± 32.7</td>
<td>312.2 ± 29.6</td>
<td>( P = .654 )</td>
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</table>

*, significant group differences; similar letter, familiar test hypothesis; SD, standard deviation; MVC, Maximal Voluntary Contraction; Nm, Newton meter; CV, Coefficient of Variation; ApEn, Approximate Entropy; nats, natural logarithmic unit.
Results

No between-groups differences in age or body mass index were found and both groups were equally physical active ($p = .54$), on average 4.8 days/week for at least 30 min per day. The control group had a physical component summary score of the Short-Form-36 questionnaire of $52.0 \pm 5.7$ (mean $\pm 1 \text{SD}$), which were comparable to the age-matched and gender-matched Danish background population ($p = .46$).

Maximal Muscle Contractions

The PD and the control group were equally strong (both extension and flexion MVC) and no difference existed in hamstring-quadriceps force ratio (Table 2).

Steady Submaximal Muscle Contractions

Statistical significantly decreased isometric tremor ApEn (difference in group means = 13.5%), reduced torque steadiness (40%) and increased coactivation (48%) were found in PD compared with controls. Data from the typical subjects are presented in Figure 1 and group averages in Table 2. No correlation existed

![Figure 1](image_url)

Figure 1 — Knee extensor torque, agonist and antagonist muscle activation from the typical control subject (A) and PD subject (B) during isometric steady knee extension.
between isometric tremor ApEn and MDS-UPDRS 3 or between torque steadiness and MDS-UPDRS 3. No between-group differences in the relative power bands of 3–6 Hz or 8–12 Hz were found. This indicated that the dampening effect of the isometric contractions had eliminated any potential between-group differences in relative power in these frequency bands.

**Powerful Submaximal Muscle Contractions.**

Data from the typical subjects are presented in Figure 2. Patients with PD had lower absolute (46%) and relative RFD (46%) compared with healthy controls. Muscle activation data further demonstrated that those patients with PD had significantly increased coactivation (97.8%) and reduced agonist muscle activation (34%) during the RFD task. No between group differences were found for overall antagonist muscle activation, electromechanical delay, premotor reaction time and reaction time (Table 2).

Backward elimination multiple regression analysis revealed that the prediction of absolute RFD, only including statistical significant parameters, consisted
of one single predictor, however, the predictor was different between groups. The predictors were agonist muscle activation \( (r^2 = .62, p = .002) \) for the PD group and extension MVC \( (r^2 = .28, p = .043) \) for the controls.

A significant negative correlation was found between absolute RFD and UPDRS 3 \( (r^2 = .32, p = .041) \).

**Discussion**

This study showed decreased knee extension isometric tremor ApEn (decreased irregularity) and reduced torque steadiness in PD compared with healthy controls. Patients with PD had markedly lower RFD and patient RFD correlated with the MDS-UPDRS 3 scores. Reduced agonist muscle activation was associated with RFD in the PD group, but not in controls. In controls, a slight association was seen between RFD and knee extension MVC.

To the best of our knowledge, only one previous study has investigated isometric tremor ApEn in PD. Vaillancourt and colleagues reported isometric tremor ApEn obtained from an index finger and thumb grip force task (Vaillancourt, Slifkin, & Newell, 2001b). In a mathematically modeled system of oscillators, greater component autonomy and isolation would result in decreased ApEn (Pincus, 1994). In general the irregularity of the motor output (e.g., isometric tremor) is expected to decrease with fewer interacting components within the motor system or in the case of only few dominant motor system oscillators. Thus, the decreased ApEn values found in patients with PD could represent the presence of pathological CNS oscillations. Our knee extension data confirmed a decreased isometric tremor ApEn in PD compared with controls, as previously reported by Vaillancourt and colleagues from an index finger and thumb grip force task, suggesting that isometric tremor ApEn are sensitive for PD. However, we did not find any significant associations between the ApEn values and the MDS-UPDRS 3 scores as reported by Vaillancourt and colleagues. The ApEn measure provides specific information of tremor irregularity, but is not necessarily directly related to motor performance in PD. Thus, we did not expect these measures to represent the same information.

The results from the powerful submaximal contractions demonstrated a markedly lower absolute and relative RFD in patients with PD. The amount of RFD deficiency for the patients with PD found in this study, corresponded to approximately half the capacity of the control group. This level of deficiency is in accordance with previously reported values ranging from 1/3–2/3 of control group levels obtained during knee extension RFD (Paasuke et al., 2004), hand grip RFD (Jordan, Sagar, & Cooper, 1992) and combined elbow RFD precision tasks (Stelmach, Teasdale, Phillips, & Worringham, 1989). In the current study, EMG was recorded during the RFD task, and large between-group differences in relative muscle activation were found. Backward elimination regression analysis suggested that overall agonist muscle activation was a moderate \( (r^2 = .62) \) single predictor of RFD in PD, whereas MVC was a slight \( (r^2 = .28) \) single predictor of RFD in the control group. When keeping in mind that no between-group differences in knee extension strength were present in this study, this suggested that during the powerful muscle contractions, the PD group could not make full use of their muscle strength capacity due to incomplete agonist muscle activation. Furthermore, the PD group had increased muscle coactivation, which also compromises RFD.
performance. In addition our data showed a slight ($r^2 = .32$) correlation between RFD and MDS-UPDRS 3. Rapid force initiation is often required in daily life to ensure coordinated and safe ambulation. The major RFD deficit found in patients with Parkinson’s disease is therefore assumed to be critical for the patients during ambulation. Thus, the evaluation of RFD could be one way to provide specific quantitative information related to patient mobility.

We did not demonstrate any changes in simple reaction time or premotor reaction time in PD compared with healthy controls. Reaction time protocols, combining simple reaction time tasks and choice reaction time tasks with different levels of precueing have been used to demonstrate whether a potential reaction time prolongation is present in PD (Jahanshahi, Brown, & Marsden, 1992). However, in accordance with our study, other studies have reported no differences (Harrison, Henderson, & Kennard, 1995; Zimmermann, Sprengelmeyer, Fimm, & Wallesch, 1992). The different results reported in the literature may be related to different patient populations and it might be hypothesized that the reported changes may have been found in a group of patients with a more advanced disease stage. However, the patients in our study were in a relatively advanced disease stage, reflected in high UPDRS scores despite the effect of medication.

In this study we found that knee extensor torque steadiness was significantly decreased in patients with PD compared with controls. Decreased torque steadiness from manual tasks has previously been reported in PD (Oliveira et al., 2008; Vaillancourt et al., 2001a) and associated with manual dexterity in healthy older adults (Marmon et al., 2011). Control of hand muscle forces is important for manual dexterity and it seems likely that decreased control of the knee joint torques may compromise locomotion e.g., foot clearance during gait and postural stability. However, this hypothesis awaits further experimental verification, as the data of the current study has only shown impaired isometric knee torque steadiness in PD. Analyses of EMG data from the current study demonstrated increased levels of muscle coactivation in the force-steadiness task in the PD group. This muscle activation strategy could be a compensating mechanism, trying to minimize underlying force fluctuations by stabilizing the knee joint. However, this strategy significantly impairs movement efficiency.

Previous studies have found decreased maximal isometric muscle strength in PD compared with controls in a variety of muscle groups (Paasuke et al., 2004; Stelmach et al., 1989), but not all studies have reached significance (Jordan et al., 1992; Pfann, Buchman, Comella, & Corcos, 2001). In the current study, where patients with PD were compared with equally physically active controls, no significantly decreased muscle strength was found. Thus, it may be that reduced muscle strength, to some extent, is secondary to PD as a consequence of reduced ambulation ability and subsequent sedentary lifestyle.

Ambulation ability is compromised in patients with PD (Pickering, Grimbergen, Rigney, Ashburn, Mazibrada, Wood, Gray, Kerr & Bloem, 2007; Canning, Ada, Johnson, & McWhirter, 2006) and seriously affects health-related quality of life (Schrag, Jahanshahi, & Quinn, 2000). In a rehabilitation perspective, physical exercise aiming to increase RFD could be a beneficial supplement in the treatment of PD. Based on our data, physical exercise aiming to increase RFD should include exercises aiming to increase quadriceps muscle activation ability. To increase quadriceps muscle activation ability, exercises should be designed to activate the
major part of the motor neuron pool at high motor unit firing frequencies. Indeed, strength training with special emphasis on motor adaptations has been reported to enhance isometric leg extension RFD and quadriceps neural activation in older adults (Hakkinen, Kallinen, Izquierdo, Jokelainen, Lassila, Malkia, Kraemer, Newton & Alen, 1998). Positive effects of resistance training in PD have been reported, however very limited data exists, for review see Falvo et al. (Falvo, Schilling, & Earhart, 2008). In addition, the use of isometric tremor analysis to gain noninvasive quantitative information of PD and muscle force control could potentially contribute to improved evaluation of disease severity, motor function and evaluation of rehabilitation regimes in PD.

It is concluded that torque measured during steady isometric muscle contractions contain information about both force variability and isometric tremor irregularity that clearly differentiate between patients with PD and healthy controls. Thus, torque steadiness was reduced and decreased isometric tremor ApEn was found in patients with PD. The severely compromised rate of force development found in patients with PD was associated with decreased levels of agonist muscle activation. In addition, patients with PD had increased muscle coactivation during steady muscle contractions, which may be a compensatory mechanism to improve steadiness. However, no deficits in the patient group were found regarding muscle strength or in electromechanical delay and reaction time in response to a simple reaction task. The findings of the current study have implications for an improved targeting of rehabilitation in PD as well as an evaluation of changes in PD related to disease progression or rehabilitation regimes.

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References


