

Ruiping Xia · W. Zev Rymer

## The role of shortening reaction in mediating rigidity in Parkinson's disease

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**Abstract** Rigidity in Parkinson's disease (PD) is defined as an increased resistance to passive movement of a joint. The plastic-type rigidity is uniform and constant throughout the entire range of motion, whereas the cogwheel-type rigidity is accompanied by tremor. Rigidity in PD has been understudied. Thus, its pathophysiological basis remains unclear. The purpose of the study is to examine neuromuscular/biomechanical properties of PD rigidity and to provide its physiological characteristics. We hypothesize that PD rigidity presents as a flattened trace of joint torque vs. angular position (torque-angle relation) of the wrist, because the forces generated by lengthening muscles are offset by activation of the antagonist, i.e. "shortening reaction" (SR). Experiments were conducted on six PD subjects medication OFF and ON. PD severity was assessed based on the unified Parkinson's disease rating scale. Each subject sat on a chair and was instructed to relax, with the wrist coupled to the device. The servomotor applied constant velocity displacement to create wrist flexion/extension. Electromyographic (EMG) responses were monitored from wrist muscles, along with position, velocity and torque. EMG magnitudes were computed over the movement period. Slopes were derived from the torque-angle trace. Results showed that SRs were routinely recorded OFF medication, but substantially

reduced ON medication. Due to the interaction of SR, torque-angle relation was flatter OFF medication and became steeper ON medication. Correlation analyses showed that a strong correlation ( $R=0.65$ ) existed between SR and torque-angle slope OFF medication, exclusively. We suggest that SR may play an important role in mediating the mechanical features of PD rigidity.

**Keywords** Anti-Parkinsonian medicine · Parkinson's disease · Rigidity · Shortening reaction · Torque-angle relation

### Introduction

Rigidity is one of the cardinal symptoms in Parkinson's disease (PD), along with bradykinesia, tremor and postural instability. Rigidity is defined, classically, as an increased resistance of a joint to passive movement. The resistance is essentially constant throughout the range of movement. This resistance is often described as "lead-pipe" or plastic in character. Cogwheel-type rigidity occurs when resistance is accompanied by tremor. Although rigidity is one of the cardinal features of PD, few studies on the genesis of rigidity have addressed the neuromuscular/mechanical mechanisms responsible for this important clinical manifestation.

Numerous studies have reported that short-latency stretch reflexes appeared essentially normal in PD (Berardelli et al. 1983; Cody et al. 1986; Meara and Cody 1993; Rothwell et al. 1983), but that the long-latency stretch reflexes were exaggerated in PD (Cody et al. 1986; Mortimer and Webster 1979; Rothwell et al. 1983; Tatton et al. 1984). Some reported a quantitative association between the long-latency responses and rigidity (Mortimer and Webster 1979; Tatton et al. 1984), whereas others found no correlation between them (Cody et al. 1986; Rothwell et al. 1983). However, long-latency response is still believed to provide a valid physiological measurement of rigidity. On the other hand, enhanced

R. Xia (✉)  
Division of Physical Therapy, University of Nebraska Medical Center,  
984420 Nebraska Medical Centre,  
Omaha, NE 68198-4420, USA  
e-mail: rxia@unmc.edu  
Tel.: +1-402-5598421  
Fax: +1-402-5598626

R. Xia · W. Z. Rymer  
Department of Physical Medicine & Rehabilitation,  
Northwestern University,  
IL, USA

R. Xia · W. Z. Rymer  
Sensory Motor Performance Program, Rehabilitation Institute of Chicago,  
IL, USA

long-latency response contributes to, but may not by itself be responsible for PD rigidity (Rothwell et al. 1983).

In addition to abnormal muscle responses to stretch, anomalous reactions to muscle shortening have also been described. Westphal (1877) reported anomalous muscular contractions in passively shortened muscles in extrapyramidal lesions. Later, Sherrington (1909) described analogous findings in spinal animals, using the term “shortening reaction” (SR). Electromyographic (EMG) recordings demonstrated that SR can be recorded in healthy individuals, but occurs widely in extrapyramidal disorders (Andrews et al. 1972; Berardelli and Hallett 1984; Berardelli et al. 1983; Rondot and Metral 1973). Some investigators suggested that SR may play a role in Parkinsonian rigidity or condition (Andrews et al. 1972; Rondot and Metral 1973). However, no study included torque-angle assessments providing objective evaluations of the resistance perceived in PD.

In spite of continued investigation, the neural mechanisms of SR remain unknown. More importantly, the impact of SR on muscle force generation or limb mechanical properties has not been addressed. Our rationale for exploring a potentially pivotal role of SR is as follows. When an active muscle is stretched, there occurs an increase in force broadly proportional to the increase in muscle length, i.e. spring-like property. Given this fundamental property, it is difficult to see how intact muscles can generate a torque that is constant throughout the range of motion. One possibility is that there is a commensurate increase in activation of the shortening opposing or antagonist muscle, i.e., an SR. Thus, the spring-like forces of the stretched muscle are offset by the forces generated from SR. Consequently, the spring-like property is modified, generating various torque-angle relations from flat to steep.

We therefore hypothesize that in PD rigidity, the force generated by muscle stretch is counteracted by the force resulting from activation of SR. This interaction induces a flattened torque-angle relation of the joint, promoting the perception of a constant or “lead-pipe” resistance, normally having a significant initial level of force as the source of resistance.

Accordingly, the objective of our study was to characterize PD rigidity by examining the muscular and mechanical behavior of wrist muscles during passive movements. We also assessed the impact of medication on SR and on the overall torque-angle relation.

## Subjects and methods

Experiments were conducted on six PD patients (four males, two females), with a mean age of  $65 \pm 20$  years. Protocols were approved by the Institutional Review Board of Northwestern University, USA, and conducted in accord with the Helsinki Declaration of 1975. All subjects gave their informed consent. Before recording, subjects received a neurological examination and Motor Examination based on the unified Parkinson’s disease rating scale (UPDRS). All subjects were treated on medication (Table 1).

Each subject sat on an adjustable chair, with the more affected hand mounted on the shaft of a DC servomotor. The axis of the wrist joint was carefully aligned with the axis of the motor. The subject’s forearm was supported horizontally and stabilized with two padded metal rings clamped to the table, preventing forearm motion.

Subjects were instructed to completely relax the wrist muscles, to the extent they were able to comply. The servomotor applied constant velocity displacement to create wrist flexion/extension. The movement amplitude was  $30^\circ$  in both directions and the velocity was  $50^\circ/\text{s}$ . Before recordings, subjects were given practice trials to accustom them to the device. Six trials were repeated and each was followed by a 2-min interval to prevent fatigue.

Subjects were initially tested with medication withheld  $-12$  h after the previous dose. After recordings were completed, subjects took their usual dose of medication in the laboratory and were re-examined clinically 60 min later. We then repeated the protocol.

Surface EMGs were recorded from wrist muscles, flexor carpi radialis and ulnaris (FCR, FCU), and extensor carpi radialis and ulnaris (ECR, ECU), using differential electrodes. Optimal electrode locations were determined by complying with the recommendations described by Perotto (1994) and confirmed with appropriate test maneuvers. EMGs were amplified ( $\times 10$  K) and band-pass filtered (bandwidth 10–250 Hz). Angular position, velocity and torque were low-pass filtered at 200 Hz prior to sampling at 500 Hz per channel, together with the EMGs.

EMGs were averaged over the full movement period in all muscles for both movements. Background muscle activity was defined as a 200-ms EMG average before movement onset. To quantify PD rigidity, torque was plotted against the joint angle. As a key measurement, the torque-angle slope was derived based on the linear regression fit to the torque-angle data. In addition, regression analysis was performed to examine the correlation between slope and normalized SR (EMG of movement phase divided by background activity).

**Table 1** Subjects’ data

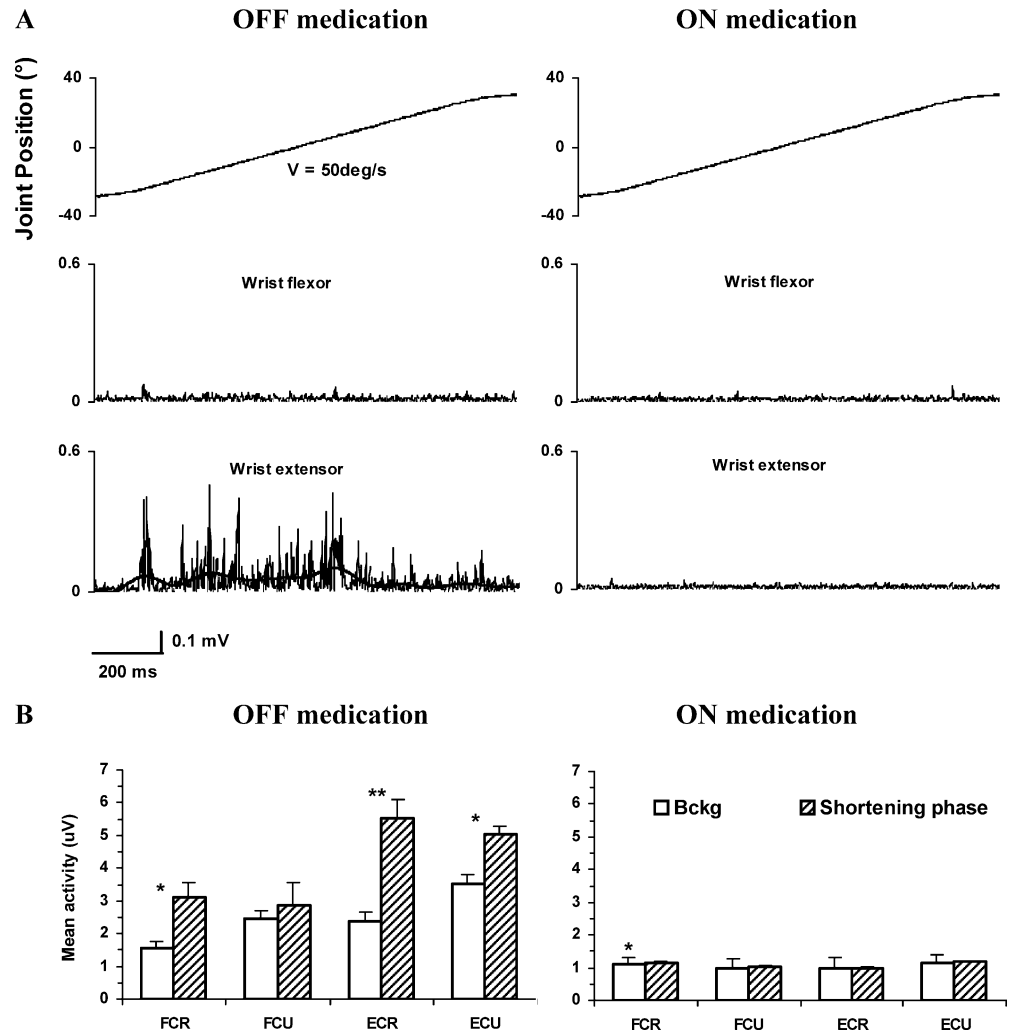
Subjects	Disease duration (yr)	Sex	Arm side	Rigidity (UPDRS) <sup>a</sup>		Medications	Dyskinesias/fluctuation <sup>b</sup>
				OFF Medicine	ON Medicine		
#1	2	F	L	2	1	S 25/100 2 × day	N
#2	2	M	R	3	3	S 25/100 4 × day	N
#3	3	M	R	3	2	P 1.5 mg 3 × day	N
#4	1	F	R	2	1	R 3.0 mg 3 × day	N
#5	5	M	R	2	1	S 25/250 3 × day	N
#6	3.5	M	L	3	3	R 5.0 mg 4 × day	N

S Sinemet, P Permax, R Requip

<sup>a</sup>UPDRS (unified Parkinson’s disease rating scale). Rigidity: 0 = absent; 1 = slight; 2 = mild to moderate; 3 = marked; 4 = severe

<sup>b</sup>Dyskinesia: a term describing abnormal involuntary movement usually seen in limbs, trunk and head

**Fig. 1** **a** SR was recorded in one subject (#4) OFF medication, and became absent ON medication during extension from 30° flexion to 30° extension at 50°/s. *Solid line*: filtered EMGs. **b** Comparison is made between background level (*blank bars*) and mean EMGs of shortening phase (*shadow bars*) in four muscles of the same subject OFF and ON medication. Shortening phases—flexion movement for flexors and extension movement for extensors. \* $p < 0.05$ , \*\* $p < 0.01$ . Error bars: s.e.m



Paired *T*-tests were performed to compare background activity with EMG of movement period. If the difference appeared statistically significant, we noted that an episode of SR occurred. No Bonferroni adjustment was applied to multiple tests (Perneger 1998). *T*-tests were also applied to examine the effect of medication on torque-angle relation.

## Results

### Characteristics of shortening reaction

SR was prominent in shortening muscles OFF medication. Conversely, SR was frequently and substantially diminished ON medication. Figure 1a is an example that SR was recorded in extensor OFF medication and abolished ON medication in one subject (#4).

Background activity was compared with EMGs, focusing on the shortening phase. Exemplar results for subject #4 are presented in Fig. 1b. SRs were recorded in FCR ( $p < 0.05$ ), ECR ( $p < 0.01$ ) and ECU ( $p < 0.05$ ) during shortening phase OFF medication. Activity of FCU increased compared with background level, though the difference was not statistically significant. SR was present

in only FCR medication ON. This pattern was typical in five subjects, but not in one subject (#6).

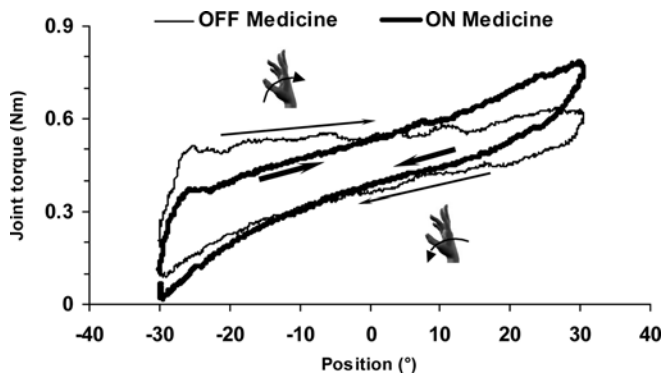
In medication OFF, SRs were present in muscles FCR ( $p < 0.05$ ), ECR ( $p < 0.05$ ) and ECU ( $p < 0.01$ ) in this subject. However, in medication ON, strong SRs occurred in four muscles ( $p < 0.001$  for all). The rigidity score remained unchanged medication OFF and ON.

Analyses of pooled data also indicated that the SRs were more pronounced in extension than flexion muscles.

Activity of each muscle during lengthening phase was also examined in both OFF and ON states. In general, low-level activities were recorded during lengthening in muscles exhibiting SR at low velocity (50°/s), being slightly higher in medication OFF than ON.

### Torque-angle relations

To evaluate the mechanical features of rigidity, torque-angle relations were examined OFF and ON medication (Fig. 2). Torque trace was clearly flatter OFF medication than ON medication for both extension (mean slope  $\pm$  sd:  $1.97 \pm 1.12$  vs.  $7.20 \pm 4.24$  mNm/°,  $p < 0.01$ ) and flexion ( $5.45 \pm 0.64$  vs.  $8.38 \pm 4.64$  mNm/°,  $p < 0.05$ ) movements in



**Fig. 2** Joint torque vs. position in five PD subjects. Torque traces were flatter OFF medication and became steeper ON medication. Initial torque was greater in medication OFF than ON state. Flexion/extension movements are indicated by hand icon

five of six subjects. This phenomenon was more evident in extension than flexion movements, presumably corresponding with the more pronounced SR in extensors than flexors. On the other hand, analysis of torque-angle relation in subject #6 showed that no significant difference of slope was observed between medication OFF and ON for either extension (mean slope  $\pm$  sd:  $2.05 \pm 0.40$  vs.  $2.08 \pm 0.28$  mNm/ $^{\circ}$ ,  $p > 0.05$ ) or flexion ( $1.87 \pm 0.56$  vs.  $1.80 \pm 0.21$  mNm/ $^{\circ}$ ,  $p > 0.05$ ) movement. Torque-angle traces were flat in both treatment states and both movement phases.

#### Correlation between normalized SR and slope

A qualitative linkage was observed between SR and torque-angle slope in that flatter slopes were associated with larger SR. To quantify this relationship, regression analyses were performed between slope coefficients and EMG responses in six subjects. Strong correlations were found in four muscles OFF medication ( $R=0.66$  for ECR,  $R=0.64$  for ECU;  $R=0.63$  for FCR,  $R=0.50$  for FCU). However, poor correlation was associated with ON medication (median  $R=0.37$ ).

## Discussion

Our main findings are that, in medication OFF, SRs are frequently recorded in wrist muscles of clinically rigid PD patients, and torque-angle relations are systematically flatter. In medication ON, SRs were substantially reduced and torque-angle traces became steeper, as predicted from our hypothesis. Findings are reinforced by the strong correlation between the torque-angle slope and SR medication OFF, exclusively. All features are consistently more evident in wrist extension than flexion muscles/movements.

Although many investigators have attempted to determine the mechanisms underlying SR, these still remain unknown. The SR was believed to be both reflexive and autogenic in origin (Berardelli and Hallett 1984; Rondot

and Metral 1973). However, Ia muscle afferents are unlikely to be responsible, as the SR is unchanged after ischemia or procaine infiltration of the antagonist, or by vibration (Andrews et al. 1972; Berardelli and Hallett 1984; Katz and Rondot 1978). Evidence against group II fibers being responsible is related to the fact that SR is found in both flexors and extensors (Andrews et al. 1972; Rondot and Metral 1973). There is evidence regarding the role of Ib afferent fiber, with findings arguing against (Matthews et al. 1990) and favoring (Berardelli and Hallett 1984) its role in mediating the SR.

Earlier investigators studied the SR under both dynamic and static conditions (Andrews et al. 1972). The dynamic component is the reaction immediately following the onset of movement. SRs recorded in our study appeared to be linked to the static component, as the response began at about 125 ms later. This latency distinguishes the SR from a voluntary movement, typically 150–200 ms in healthy individuals and at least 250–300 ms in PD.

Torque-angle measurements provide an objective evaluation of mechanical stiffness, and potentially, of rigidity. Flattened torque-angle relation is observed OFF medication (Fig. 2). The initial torque, coupled with the flat torque-angle traces, presumably generates the lead-pipe resistance perceived by examiner in clinical evaluation. After medication took effect, the torque-angle trace became steeper. On the other hand, when medication produced no effect on SRs, as appeared in subject #6, torque-angle traces were essentially parallel to each other medication OFF and ON.

In combination with EMG data, we suggest that flattened torque trace is a result of counteracting force generated by SR. This notion is further supported by the prevalence of SR in extension muscles and smaller torque-angle slopes in the extension phase as well as the stronger correlation of SR and slope in extensors.

In general, SR shares certain features with descriptions of Parkinsonian rigidity in that both are poorly related to the rate of displacement (Rondot and Metral 1973) and modulated with reinforcement of the opposite hand (Andrews et al. 1973). Previous investigators found correlations between SR and clinical improvement in Parkinsonism (Andrews and Burke 1973).

Our data indicate that there is at least a qualitative relation between SRs and clinical improvement of rigidity induced by medication. These findings lead us to suggest that SR may play a key role in mediating clinical rigidity of PD. Given the population number in our study, our hypothesis needs to be tested on a larger PD population with a broader range of clinical features.

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## References

- Andrews CJ, Burke D (1973) Quantitative study of the effect of L-dopa and phenoxybenzamine on the rigidity of Parkinson's disease. *J Neurol Neurosurg Psychiatry* 36:321–328
- Andrews CJ, Burke D, Lance JW (1972) The response to muscle stretch and shortening in Parkinsonian rigidity. *Brain* 95:795–812
- Andrews CJ, Neilson PD, Lance JW (1973) Comparison of stretch reflexes and shortening reactions in activated normal subjects with those in Parkinson's disease. *J Neurol Neurosurg Psychiatry* 36:329–333
- Berardelli A, Hallett M (1984) Shortening reaction of human tibialis anterior. *Neurology* 34:242–245
- Berardelli A, Sabra AF, Hallett M (1983) Physiological mechanisms of rigidity in Parkinson's disease. *J Neurol Neurosurg Psychiatry* 46:45–53
- Cody FWJ, MacDermott N, Matthews PBC, Richardson HC (1986) Observations on the genesis of the stretch reflex in Parkinson's disease. *Brain* 109:229–249
- Katz R, Rondot P (1978) Muscle reaction to passive shortening in normal man. *Electroencephalogr Clin Neurophysiol* 45:90–99
- Matthews PBC, Cody FWJ, Richardson HC, MacDermott N (1990) Observations on the reflex effects seen in Parkinson's disease on terminating a period of tendon vibration. *J Neurol Neurosurg Psychiatry* 53:215–219
- Meara RJ, Cody FWJ (1993) Stretch reflexes of individual Parkinsonian patients studied during changes in clinical rigidity following medication. *Electroencephalogr Clin Neurophysiol* 89:261–268
- Mortimer JA, Webster DD (1979) Evidence for a quantitative association between EMG stretch responses and Parkinsonian rigidity. *Brain Res* 162:169–173
- Perneger TV (1998) What's wrong with Bonferroni adjustments. *Br Med J* 316:1236–1238
- Perotto AO (1994) Anatomical guide for the electromyographer: the limbs and trunk. Charles C Thomas, Springfield, IL, USA, pp 141–171
- Rondot P, Metral S (1973) Analysis of the shortening reaction in man. In: Desmedt JE (ed) *New developments in electromyography and clinical neurophysiology*, vol. 3. Karger, Basel, pp 629–634
- Rothwell JC, Obeso JA, Traub MM, Marsden CD (1983) The behaviour of the long-latency stretch reflex in patients with Parkinson's disease. *J Neurol Neurosurg Psychiatry* 46:35–44
- Sherrington CS (1909) On plastic tonus and proprioceptive reflexes. *Quart J Exp Physiol* 2:109–156
- Tatton WG, Bedingham W, Verrier MC, Blair RD (1984) Characteristic alterations in responses to imposed wrist displacements in Parkinsonian rigidity and dystonia musculorum deformans. *Can J Neurol Sci* 11:281–287
- Westphal C (1877) Unterschenkelphänomen und Nervendehnung. *Arch Psychiat und Nervenkr* 7:666–670