ROTATIONAL EQUILIBRIUM DURING MULTI-DIGIT PRESSING AND PREHENSION

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Abstract

We review a series of studies on the production of moments (keeping rotational equilibrium) by sets of fingers in pressing and static prehension tasks. These studies show that stabilization of the moment of a couple produced by a set of digits is seen in a variety of maximal and submaximal accurate total force production tasks that have no requirements for the moment. Analysis of covariation of finger forces and of elemental independent variables to fingers (finger modes) across trials at a novel, unusual force production task shows stabilization of the total free moment from early trials and over several practice sessions. In contrast, the total force requires extensive practice to be stabilized. Similar results were obtained in persons with Down syndrome during easier tasks. During prehension, elemental variables to digits (forces and coordinates of their points of application) show dependences on the external load and external torque that suggest the presence of two multi-digit synergies whose purpose is to assure a certain grip force and a certain total moment respectively. A similar conclusion has been drawn based on analysis of covariation of elemental variables during multiple repetitions of static prehension tasks with unchanged external load and torque. Elderly persons show impaired production of both maximal and submaximal moments that goes beyond their documented loss of muscle force. We conclude that moment production (keeping rotational equilibrium) is a central constraint in a variety of multi-digit tasks that has received relatively little attention. In particular, analysis of digit interaction for moment production during handwriting could signify a major step towards understanding the control of this human hand action.

Introduction

Multi-digit action has been used in many studies as an example of the famous problem of motor redundancy, known also as the Bernstein problem (Bernstein 1967; Turvey 1990). Most of these studies focused on the production of certain task-specific levels of the total grip force and slipping prevention under changes in such factors as the load force, friction between the fingertips and the object, and others (Edin et al., 1992; Cole and Johansson 1993; Flanagan and Wing 1997; Santello and Soechting 2000; Baud-Bovy and Soechting 2001). Relatively little attention has been paid to the rotational equilibrium of the hand-held objects, i.e. production of force moments acting on the objects, despite the obvious importance of the rotational equilibrium for everyday prehensile tasks. Within this paper, we mostly consider moment of a couple produced by a set of digits and will, for brevity, refer to it as simply moment. In particular, we will focus on moments that generate a rotational effect about a longitudinal axis of the hand typically associated with the hand pronation or supination.

Many everyday tasks impose rather strict requirements for the production of moment, while the total force only needs to be within certain, relatively broad margins. For example, during drinking from the glass, the total grip force needs to be above the slipping threshold and below the crushing threshold – a rather wide range. In contrast, the total moment needs to be controlled precisely to avoid spilling the contents of the glass. During writing, the grip force needs only to be large enough to prevent the implement from falling out of the hand. In contrast, modulation of the moment defines the trajectory of the tip of the implement and unique characteristics of the handwriting (Latash et al. 2003).

Despite the apparent importance of stabilization of time profiles of the total moment during prehensile tasks, until recently, studies of the moment production by sets of digits were all but lacking. The main purpose of this paper is to review series of recent studies related to multi-finger moment production and to present novel data on the effects of aging and practice on this important component of the hand function.

Principle of minimization of secondary moments

Studies of patterns of the force sharing among fingers during multi-finger pressing tasks suggested a principle of minimization of secondary moments (Z.-M. Li et al. 1998). This principle states that the total force is shared among the fingers in ways that reduce pronation/supination moments acting on the hand. When a subset of fingers within the human hand is explicitly involved in a force production task, other fingers also produce forces. This phenomenon has been termed *enslaving* (Z-M Li et al. 1998, Ohtsuki 1981; Kinoshita et al. 1996). A study of the patterns of enslaving during maximal voluntary contraction (MVC) tasks have also suggested that these patterns were at least partly directed at reducing the total pronation/supination moment that would have been observed without the enslaving (Zatsiorsky et al. 2000).

These observations were extended in two-hand multi-finger force production tasks (S. Li et al. 2000). In those studies, patterns of bilateral effects (cf. Ohtsuki 1983; Vint et al. 1999; reviewed in Archontides and Fazey, 1993) suggested a reduction of the overall moment in the frontal plane acting on the body. This idea was corroborated in studies when the positions of the two hands with respect to the trunk were asymmetrical (S. Li et al. 2001).

In both one-hand and two-hand force production studies, the subjects were typically required to produce maximal forces by subsets of fingers. The subjects were never given any instruction or feedback on moment production. Minimization of secondary moments under such conditions has suggested that keeping a value of the moment produced by a set of fingers may be an important factor defining patterns of finger forces even in the absence of explicit moment requirements.

Uncontrolled manifold approach to moment production

Further, multi-finger interaction during force production tasks was studied using the framework of the uncontrolled manifold (UCM) hypothesis (Scholz and Schoner 1999; Latash et al. 2001, 2002). The hypothesis assumes that the controller works in a space of independent elemental variables and establishes in that space a subspace (a UCM) corresponding to a value of an important performance variable. Then, variability of elemental variables is primarily restricted to the UCM.

In analysis of multi-finger pressing tasks, elemental variables could not be associated with forces produced by individual fingers because of the mentioned phenomenon of enslaving, which makes finger forces dependent on each other. To overcome this problem, another set of variables was introduced called force modes (Latash et al. 2001; Scholz et al. 2002; Danion et al. 2003). These are hypothetical independent variables corresponding to desired involvement of individual digits into force production tasks. Multi-finger synergy has been defined as a covariation of force modes that stabilizes a particular value of an important performance variable such as the total force or the total moment. Correspondingly, two types of synergies have been analyzed, total force stabilizing synergies and total moment stabilizing synergies. The two types of synergies are in competition because the former favors negative covariation among finger forces, while the latter favors positive covariation of the forces produced by subgroups of fingers that produce moments in opposite directions with respect to a pivot point. This is particularly obvious in two-finger tasks, where there are only two variables that can covary either negatively to stabilize their summed output (total force) or positively to stabilize the difference between the outputs (related to total moment with respect to the midpoint between the points of application of the two forces).

In experiments with relatively fast force production, the total moment was stabilized better than the total force by covariation of force modes to individual fingers (Latash et al. 2001; Scholz et al. 2002). This happened despite the fact that the production of particular patterns of the total force was an explicit task component with continuous visual feedback presented to the subjects, while the total moment was not even mentioned and no visual feedback was presented. Total force stabilization was more pronounced during slow force production tasks performed under continuous visual feedback on the total force. However, even during the slowest trials, positive covariation of individual finger forces was seen during the first half a second, later turning into negative covariation adequate for total force stabilization (Shim et al. 2003).

Effects of practice on force/moment stabilization during pressing tasks

The observations of better moment stabilization in most studies have led to a hypothesis that patterns of covariation of force modes are conditioned by the everyday experience over the lifetime, which, as mentioned in the Introduction, commonly places more strict requirements on moment variations. Three experiments were run to study whether patterns of finger interaction can change with practice.

In the first study (Latash et al. 2003), subjects practiced for about 1.5 hours (200 trials) a ramp total force production task while pressing with three fingers on individual force sensors.

The task was complicated by two factors. First, the frame with the sensors rested on a very narrow support placed under the middle finger. Second, in each trial, unexpectedly, a transcranial magnetic stimulus (TMS) was applied over the contralateral primary motor cortical area. The stimulus induced a quick jerk of the fingers and perturbed both the total force and the total moment. Effects of practice were assessed using brief series of unperturbed ramp trials. Over time subjects improved their overall tracking performance: the variance of the total force trajectory declined by 60% after the first 100 trials, but there was little additional improvement after the second 100 trials. Variance in the force finger space related to the total moment with respect to the pivot also showed a decline during the first half of practice and minimal further changes during the second half. In contrast, finger force variance that did not affect either total force or total moment showed no changes after the first 100 trials and a decline during the second 100 trials. This variance component quantified per finger was significantly larger than those related to the total force and total moment. TMS induced changes in the finger forces also showed a gradual change. The overall force response declined. Besides, the differences in the responses of the index and ring fingers, which perturbed the total moment with respect to the pivot, declined as well. This study has demonstrated that a relatively brief practice is sufficient to induce plastic changes in neural structures responsible for the TMS induced responses.

In another study (Latash et al. 2002; Scholz et al. 2003), effects of practice on finger interaction in persons with Down syndrome (DS) were studied. In that study, the participants were asked to produce ramp profiles of the total force while pressing on force sensors with all four fingers of the dominant hand without any instability. Prior to practice, persons with DS showed predominantly positive covariation among individual finger forces (and force modes) leading to destabilization of the total force, while the pronation/supination moment was stabilized. As in other studies, the subjects were given feedback on the total force but not on the moment. After two days of practice, persons with DS improved their overall performance and started to show covariation of force modes, which stabilized the total force profile. Notably, there was no deterioration in the moment stabilization.

In the third study (Kang et al. 2004), subjects practiced a multi-finger force production task. The task was purposefully made very unusual and hard to make sure that there was sufficient room for improvement in patterns of finger coordination. The subjects were required to produce a ramp profile with a signal (task force, F_{TASK}) representing the sum of the forces produced by asymmetrical finger pairs in the two hands (for example, the index and ring fingers of one hand plus the middle and little fingers of the other hand), from which the forces produced by the other four fingers were subtracted. Finger coordination was studied using the UCM hypothesis framework. Prior to practice, subjects showed high error indices and failed to show stabilization of each hand's contribution to F_{TASK} by covariation of force modes to the hand's fingers. However, the pronation-supination moment was stabilized by the fingers of each hand despite the lack of instructions on this moment. Over two days of practice, the performance of the subjects improved considerably. This was accompanied by the emergence of within-a-hand force stabilization for each of the two hands without deterioration of moment stabilization. This is not trivial because of the mentioned competition between force and moment stabilization.

Taken together, these three studies show that finger coordination during multi-finger force production tasks can change readily under practice. As the first study suggests, major changes in the finger coordination happen after only 100 trials (under one hour) and are accompanied by plastic changes in neural structures responsible for the TMS induced finger responses. Even very unusual patterns of finger interaction (as in the third study) or patterns of finger interaction in atypical persons (as in the second study) can be learned over the course of a couple of days. It is therefore quite conceivable that moment stabilization observed in most studies is conditioned by the lifetime experience. However, most of the mentioned studies used a rather unusual task of pressing with several fingers on fixed sensors. So, the next step was to analyze moment stabilization during more natural prehensile tasks.

Moment production during static prehension

Holding an object with a prismatic grasp (the thumb is opposing the four fingers) has been frequently analyzed as a task controlled in a hierarchical manner. At a higher level of the hierarchy, adequate forces and moments for the thumb and the virtual finger (VF) are defined. VF is an imaginable digit whose mechanical action on the hand-held object is equivalent to the summed action of all four fingers (Cutkosky, Howe 1990; Mackenzie, Iberall 1994). At the lower level, the action of the VF is distributed among the actual fingers leading to the generation of their forces and moments. This scheme does not necessarily imply that the control levels deal directly with forces and moments. Such force-control view has been criticized recently (Ostry & Feldman 2003). The nature of control variables at both levels is unknown; they are likely to be related to positional variables, as suggested within the equilibrium-point hypothesis (Feldman 1986; Latash 1993; Feldman and Levin 1995).

Recently, we have performed a series of studies of static prehensile tasks, where moment stabilization was an explicit task component. These studies analyzed two-dimensional force and moment production while holding an instrumented handle in a prismatic grasp against an external load and moment. Figure 1 illustrates a typical task. To hold the handle statically, the subject needed to apply individual digit forces to satisfy three constraints expressed as equations of statics:

$$F_i^n + F_m^n + F_r^n + F_l^n + F_{th}^n = F_{vf}^n = F_{th}^n \tag{1}$$

$$F_i^t + F_m^t + F_r^t + F_l^t + F_{th}^t = F_{vf}^t + F_{th}^t = L \tag{2}$$

$$-T = \underbrace{F_{th}^n d_{th} + F_i^n d_i + F_m^n d_m + F_r^n d_r + F_l^n d_l}_{\text{Moment of the normal forces} \equiv M^n} + \underbrace{F_{th}^t r_{th} + F_i^t r_i + F_m^t r_m + F_r^t r_r + F_l^t r_l}_{\text{Moment of the tangential forces} \equiv M^t} \tag{3}$$

where the subscripts *th, i, m, r* , and *l* refer to the thumb, index, middle, ring, and little finger, respectively; the superscripts *n* and *t* stand for the normal and tangential force components, respectively; and coefficients *d* and *r* stand for the moment arms of the normal and tangential forces with respect to a pre-selected pivot point, respectively. F_{vf}^n and F_{vf}^t are the virtual finger normal and tangential forces (the resultant normal and tangential force exerted by the four fingers). *T* is the external moment applied to the handle; *L* is external load. As mentioned in an earlier study (Zatsiorsky et al. 2002), the third constraint may be viewed as central because it unites all the elemental variables (digit forces and points of their application) while each of the other two constraints deals with subsets of these variables.

In one of the studies (Zatsiorsky et al. 2003), the subjects were required to hold the handle against an external load (*L*) and torque (*T*), the magnitudes of *L* and *T* varied across trials, and changes in elemental variables were analyzed. When the task parameters were varied, regular conjoint changes of the digit forces (prehension synergies) were observed. These synergies represented preferred solutions used by the subjects to satisfy the mechanical requirements of the tasks. All elemental variables showed significant changes with T and L;

however, there were no significant interactions between these two factors. Figure 2 illustrates this result for the moment produced by the tangential force of the virtual finger. This result has suggested that variations in the total grip force applied by the digits (Eq. 1) and in the total moment (Eq. 3) occur largely independent of each other despite the fact that the two constraints share a number of elemental variables.

This conclusion is in a good correspondence with a principle of superposition suggested recently in robotics for the control of multi-element systems (Arimoto et al. 2001). According to this principle, some skilled actions can be decomposed into several elemental actions that are controlled independently by separate controllers. In particular, it has been shown that a dexterous grasp and manipulation of an object by two soft-tip robot fingers can be realized by a linear superposition of two commands related respectively to stable grasp and regulation of the orientation of the object. Such a decoupled control decreases the computation time.

To analyze a possibility that the principle of superposition is also applicable to human prehension, another study was performed. In that experiment, repetitive trials at the same task (same combinations of *L* and *T*) were associated with variations in the elemental variables that showed reproducible relations when analyzed at the level of forces and moments produced by the thumb and VF. Correlation analysis among the elemental variables has shown that they formed two subsets (Figure 3). The variables within each subset highly correlated with each other over repetitions of a task while the variables from different subsets did not show significant correlations. The first subset included normal forces of the thumb and VF (panel 1A). The second subset included tangential forces of the thumb and VF, the moments produced by the tangential and normal forces, and the moment arm of the VF normal force. In particular, trial-to-trial changes of the VF normal force F_{vf}^{n} did not correlate with the variations of the VF moment of the normal force M_{vf}^{n} (panel 2A). Because the moment of the normal force is the product of the F_{vf}^{n} and its moment arm, this lack of correlation is counter-intuitive. On the other hand, high correlations between the moment produced by tangential forces $\boldsymbol{M}^{t}$ and tangential force of the virtual finger F_{th}^{t} and M_{vf}^{n} was found (panel B).

Some of the relations found in the two studies are necessitated by the mechanical requirements of the task (Eqs 1-3). For example, the magnitudes of the normal forces of the thumb and the VF should be equal to prevent the object from moving. Similarly, the sum of the thumb and VF tangential forces should be equal to the external load. Other relations, however, are not obviously dictated by the mechanics of the task. In particular, the task mechanics does not prescribe the magnitude of either of the tangential forces, thumb or VF, only their sum. It also does not prescribe their trial-to-trial variations. The lack of correlation between the normal force $\boldsymbol{F}_{vf}^{n}$ and the moment that the force generates ($\boldsymbol{M}_{vf}^{n}$, Figure 2b) suggests that the CNS does not use all mechanically possible options to control $\boldsymbol{M}_{vf}^{n}$. Mechanically, the trial-to-trial tuning of the $\boldsymbol{M}_{vf}^{n}$ can be achieved by variations of the $\boldsymbol{F}_{vf}^{n}$ (i.e. by proportional changes of all normal finger forces) but the CNS does not use this option. Instead it mainly controls the moment arm by adjusting the sharing pattern of finger forces.

On the whole, the data show that elemental variables are organized in null spaces and thus support the UCM hypothesis. The results of both experiments suggest that the principle of superposition (Arimoto et al. 2001) is valid for the control of multi-finger prehension in humans. Forces and moments of individual digits are defined by two independent commands: “Grasp the object stronger/weaker to prevent slipping” and “Maintain the rotational equilibrium of the object”. The effects of the two commands are summed up.

Changes in digit interaction during prehension tasks with age

Aging leads to a decline in hand dexterity and strength (Hackel et al., 1992; Rantanen et al. 1999; Francis and Spirduso 2000; Boatright et al. 1997). This is associated with changes in the neuromuscular apparatus such as a drop in the number of motor units, an increase in the size of the motor units and a general slowing of their contractile properties (Owings, Grabiner, 1998; Kamen et al. 1995; Kernell et al. 1983; Larsson and Ansved 1995). In earlier studies, we have shown that these peripheral changes are accompanied by changes in indices of finger interaction during multi-finger force production tasks (Shinohara et al. 2003a,b, 2004). However, there have been no studies that would address possible age-related changes in the ability to produce moments during prehension tasks.

In a recent study, two groups of subjects, young and elderly, were asked to perform a set of prehension tasks that required both maximal and submaximal accurate production of forces and moments. During tasks that required the production of maximal force or maximal moment by all the digits, young subjects were predictably stronger than elderly. However, a greater age-related deficit was seen in the maximal moment production tests.

Accurate force/moment production trials involved, in particular, the production of a ramp profile of the normal force produced by all four fingers while keeping the orientation of the handle against a constant external torque that could act either in pronation or in supination. During these trials, elderly persons were less accurate in the production of both total moment and total force. They produced higher antagonistic moments, i.e. moments by fingers that acted against the required direction of the total moment in an apparent attempt to stabilize the orientation of the handle.

Both young and elderly subjects showed negative covariation of finger forces across repetitions of the ramp force production task. In accurate moment production tasks, both groups showed negative covariation of two components of the total moment, those produced by the normal forces and produced by the tangential forces (see Eq. 3). However, elderly showed lower values of the indices of both finger force covariation and moment covariation. We conclude that age is associated with an impaired ability to produce both high moments and accurate time profiles of moments. This impairment goes beyond the well documented deficits in finger and hand force production by elderly persons. It involves worse coordination of individual digit forces and of components of the total moment.

Concluding comments

A number of important points related to the production of moments by the human hand have emerged from the reviewed series of studies:

First, we have shown that stabilization of the moment produced by a set of digits can be seen in a variety of tasks, even in those where moment stabilization is not a part of the task. Moreover, moment stabilization is frequently seen as a default mode early in trials that require production of a particular time profile of the total force, not moment.

Second, studies of the effects of practice on finger interaction have shown quick changes in indices of finger interaction in a task specific way. These changes were likely accompanied by plastic changes in neural structures involved in the generation of finger responses to stimulation of the primary cortical areas. Most studies of the effects of practice did not require the subjects to stabilize the total moment produced by the digits. However, moment stabilization persisted invariably.

Third, moment stabilization during prehension tasks seems to result from a central organization of a null space in the space of elemental variables. It is a component of prehension that seems to be organized in parallel to another component, grip force control, corresponding to the principle of superposition.

Fourth, age results in worse control of the moment by the combined action of the human digits. This may be a major contributor to the deterioration of the human hand function with age.

Studies of moment production by sets of human digits are at their infancy. These studies require more sophisticated methods and analysis as compared to more traditional studies of force production. In particular, analysis of digit interaction for moment production during handwriting could signify a major step towards understanding the control of this human hand action. However, such an analysis would require a possibility to measure all the forces and moments applied to the implement by the human hand. This is currently a technological challenge.

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Figure Captions:

<u>Figure 1:</u> An illustration of the apparatus used in prehension studies. The T-shaped attachment allowed to change the load and the torque it produced independently. Each digit pressed on a transducer that measured the three force and three moment components.

<u>Figure 2</u>: The dependence of the moment produced by the tangential force of the virtual finger ($\boldsymbol{M}_{vf}^{t}$) on the external torque for four different loads for a representative subject. Note that $\boldsymbol{M}_{vf}^{t}$ depends on both torque and load without an interaction.

<u>Figure 3</u>: Examples of correlations among the elemental variables in a representative subject. The variables formed two subsets. Panel 1A illustrated the first subset, which defined the grip force and stabilized the handle in the horizontal direction. Panel 2A illustrates the counter-intuitive lack of correlation between the normal force of the virtual finger ($\boldsymbol{F}_{vf}^{n}$) and the moment it produced ($\boldsymbol{M}_{vf}^{n}$). Panels 1B and 2B illustrate relations among a subset of variables that all contributed to stabilization of the total moment.

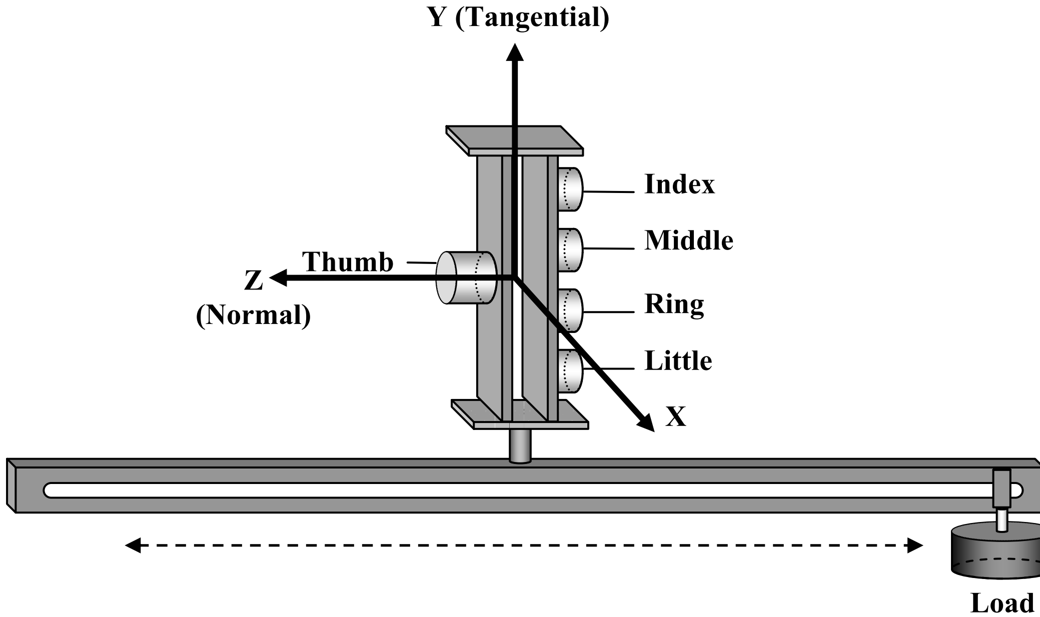
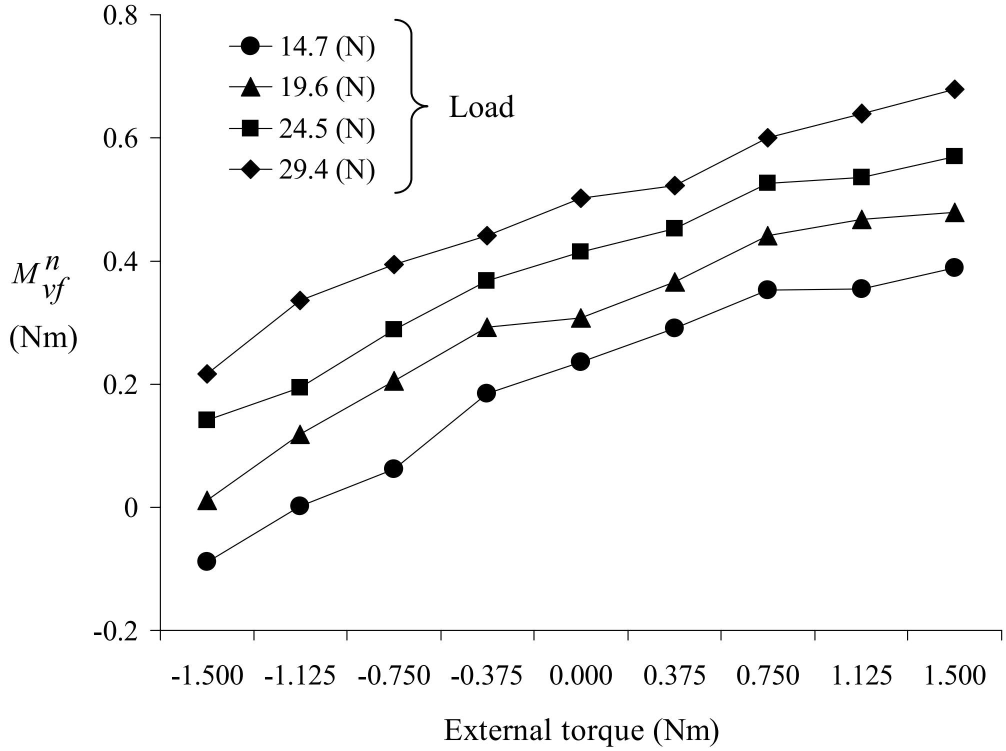


Figure 1



0.8
0.6
0.4
0.2
0
-0.2
14.7 (N)
19.6 (N)
24.5 (N)
29.4 (N)
Load
M_{vf}^{n}
(Nm)
-1.500
-1.125
-0.750
-0.375
0.000
0.375
0.750
1.125
1.500
External torque (Nm)

Figure 2

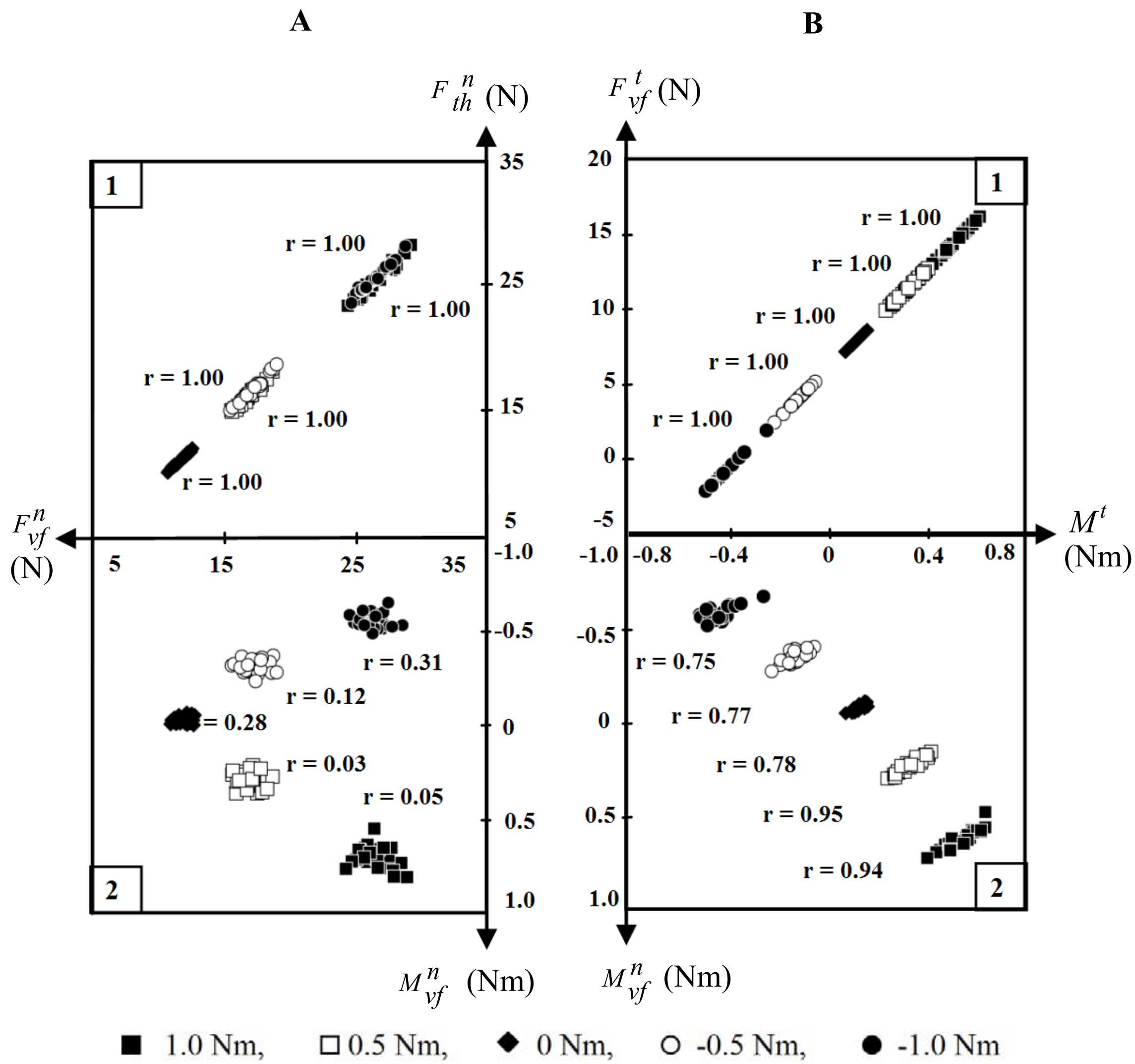

A
B
F^{n}_{th} (N)
F^{t}_{vf} (N)
1
2
35
25
15
5
20
15
10
5
0
-5
r = 1.00
r = 1.00
r = 1.00
r = 1.00
r = 1.00
r = 1.00
r = 1.00
r = 1.00
r = 1.00
r = 1.00
F^{n}_{vf} (N)
5
15
25
35
-1.0
-0.8
-0.4
0
0.4
0.8
M^{t} (Nm)
-0.5
0
0.5
1.0
r = 0.31
r = 0.12
= 0.28
r = 0.03
r = 0.05
r = 0.75
r = 0.77
r = 0.78
r = 0.95
r = 0.94
M^{n}_{vf} (Nm)
M^{n}_{vf} (Nm)
1.0 Nm,
0.5 Nm,
0 Nm,
-0.5 Nm,
-1.0 Nm

Figure 3