Measurement of the Comfort of Automobile Clutch Pedal Actuation

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In the field of ergonomics, a growing area of interest is that of the comfort associated with human movement in and around vehicles. There have been few studies to date which have evaluated the comfort associated with human motion when using vehicle commands such as the steering wheel, gear shift and pedals. This paper presents a study of clutch pedal actuation in terms of human comfort. A pedal transducer was designed and manufactured, and the static and dynamic characteristics of clutch disengagement were measured for 2 automobiles and a test jury of 13 people. The comfort associated with clutch disengagement was evaluated by means of a three part questionnaire. Force data measured normal to the pedal surface and postural body angles were correlated against the responses to the questions of the comfort questionnaire. Three parameters were found to strongly correlate with the subjective responses, these were the change of trunk-thigh angle $\Delta\alpha$ from the beginning of the clutch pedal stroke to the end, the maximum force achieved during the end-of-travel impact, and the average slope of the force-displacement curve during the initial disengagement phase. These quantities appear important in determining clutch actuation comfort and need to be monitored by any device acting as a “clutch meter”.

Introduction

Having achieved important results in areas such as postural comfort [6,16,21] and strength [3,10,17], vehicle ergonomists have begun dedicating effort in recent years towards the study of human motion in and around the vehicle [4,14-15,17,20]. More knowledge regarding human movement strategies [12] and movement comfort [18] would be most beneficial towards the definition of improved design guidelines for vehicles.

This paper presents an analysis of automobile clutch pedal actuation. The study addresses the relationship between the subjectively perceived comfort and the mechanical and postural quantities which define the clutch disengagement process as summarised in Figure 1. Force and acceleration data were measured at the clutch pedal and subjective responses were collected from the test subjects. This permitted a statistical correlation analysis across all pairings of mechanical data versus subjective data, and between all pairings of postural data and subjective response. This paper presents the results of the force and postural angle analysis. The results of the analysis of the pedal acceleration data will be the subject of a separate, future paper. The analysis described in the following sections represents a first step towards defining design guidelines and perhaps a “clutch meter” device.

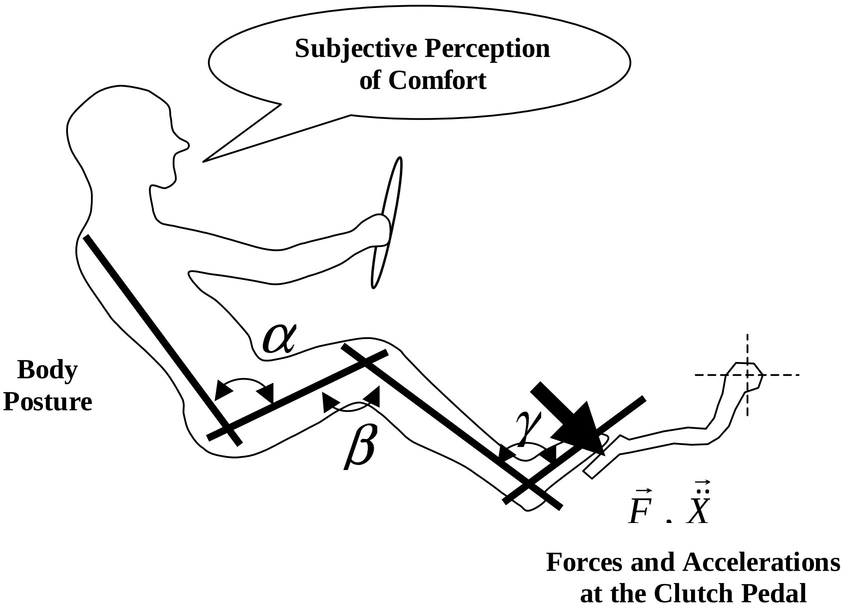


Figure 1) The clutch actuation problem.

Measurement Methods

This study measured the normal forces at the clutch pedal both statically and dynamically. A static test of each automobile's clutch pedal was performed using a spring loaded force gauge (Salter Model 16 Tension and Compression Tester) which was pushed against the pedal surface to measure the force. A gravity goniometer was attached at a convenient point along the pedal body to measure the angle ϕ from which the pedal rotation angle θ could be calculated.

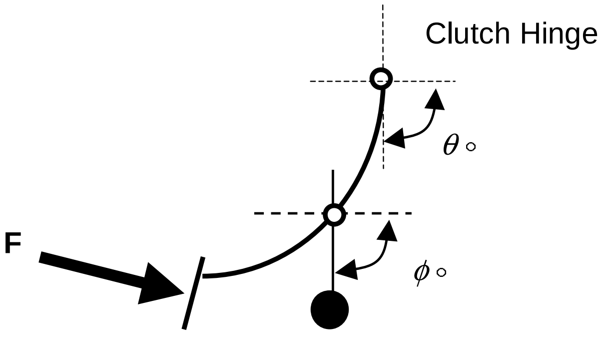


Figure 2) Static measurements of clutch force.

The force gage was pressed against the centre of the clutch pedal at 90 degrees to the surface. Five force measurements were attempted at roughly 2 degree intervals, but it was not possible to complete all the measurements due to the difficulty of manually stabilising the force gauge against the pedal while working inside the automobile. Those angles for which it was possible to obtain three measurements were averaged together to obtain the static force-deflection curve.

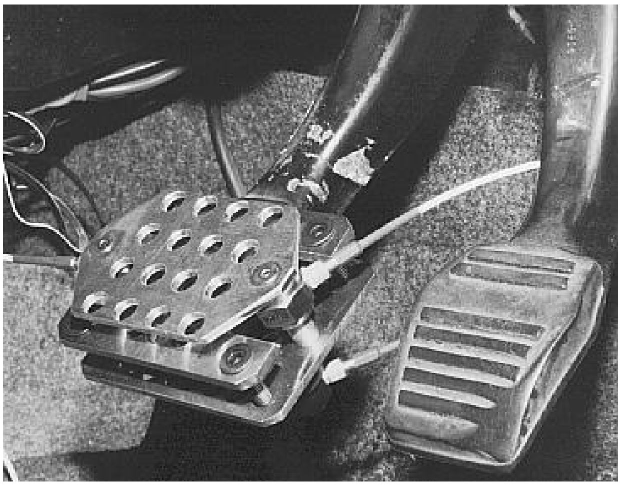


Figure 3) Clutch pedal sensor.

Dynamic measurements were made by means of a sensor designed for this study which is shown in Figure 3 mounted on the clutch pedal of a Ford Fiesta. The sensor consisted of two steel attachment plates which were tightened together to trap the automobile clutch pedal, thus fixing the sensor to the pedal. A third steel plate was separated from the other two by two B&K type 8200 piezoelectric force sensors. One force sensor was located on each side of the pedal centreline, thus the total normal force acting on the pedal sensor was calculated during post processing as

$$F_{total} = F_{left} + F_{right}$$

A PCB model 336C04 piezoelectric accelerometer was attached to the back surface of the pedal sensor to measure the linear acceleration during actuation. The whole pedal sensor unit weighed 250 grams. The charge signal from each force sensor was amplified by means of B&K type 2635 amplifiers while the PCB accelerometer furnished a voltage signal directly due to the sensor's ICP amplifier and the use of a PCB model 480D09 power supply. The force and acceleration signals were recorded by means of an 8 channel KYOWA RTP-610 analogue tape recorder. Signal analysis was performed in the laboratory using the Time Data Processing Monitor (TMON) of the LMS CADA-X revision 3.4 software system [11]. The LMS software was run on an HP 715/64 workstation with a Difa Measuring Systems SCADAS II front-end unit. After a series of preliminary evaluations, it was found that a sampling rate of 1000 Hz (500 Hz cut-off) was necessary to obtain precise values for the peak force during end-of-travel impact.

Subjective comfort was evaluated by means of a 3 part questionnaire. The questionnaire was developed by performing tests with 3 people prior to the study described in this paper. The questionnaire sections were:

- A general comfort evaluation form
- A body part discomfort form
- A pedal mechanical evaluation form

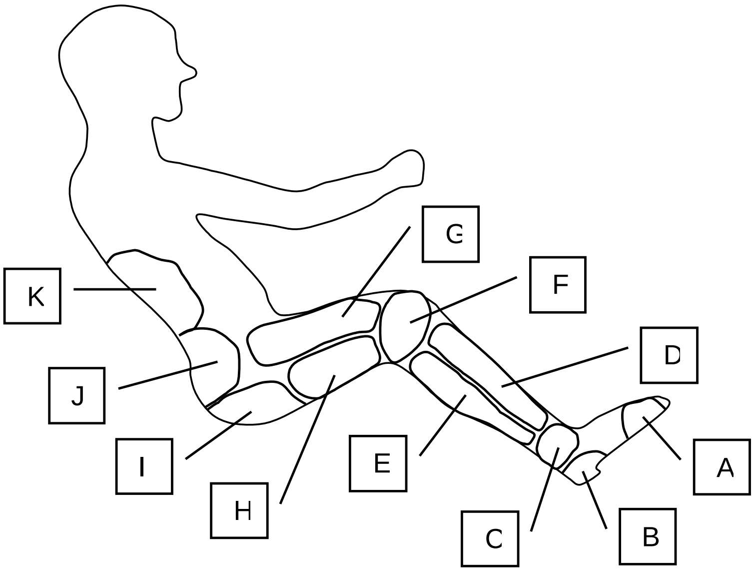
Most questions were presented using a two-step Likert-type format. A two-step scale was used to extend the optimum number of response options beyond the 5 to 7 range typical of one-step Likert scales [5,13]. Question number 3 of the general comfort evaluation form is given as an example in Figure 4.

How do you rate the general level of comfort when actuating the clutch pedal?

very uncomfortable		**uncomfortable**		**average**		**comfortable**		**very comfortable**	
1	2	3	4	5	6	7	8	9	10

Figure 4) A question from the general comfort section of the questionnaire.

The body part discomfort form asked the test subjects to state the level of comfort associated with each of the 11 body regions identified in Figure 5. Each region had an associated 10 point scale like the one of Figure 4. Eleven regions were used so as to localise the body sensations precisely, with specific muscle packs being targeted in the case of the leg segments.



A: Metatarsal
B: Calcaneus
C: Ankle
D: Upper Leg
E: Lower Leg
F: Knee
G: Upper Thigh
H: Lower Thigh
I: Ischia
J: Lumbar
K: Thoracic

Figure 5) Body regions evaluated in the body part discomfort form.

Three body angles were measured and analysed in this study to define the seated posture of the test subject. The angles were α, β and γ which are defined in Figure 1 and which were measured by means of a full circle goniometer with 12 inch arms. Each angle was measured for each subject in two test positions, the beginning and the end of the clutch pedal stroke.

The Experiment

Two automobiles were selected for this study. The first was a 1982 Ford Fiesta 1.1L hatchback which was selected because it had a heavy clutch with high breaking friction, and strong end-of-travel impacts. The second automobile was a 1987 Volvo 340 DL 1.4 L which presented smooth clutch actuation with relatively low forces and weak end-of-travel impacts.

Consideration of the nature of the tests suggested that both individual differences and learning effects would probably be present in the data of the subjective questionnaires. Comparison of the clutch pedal actuation task to other movement studies did not provide clear indications as to whether a between-subjects or a within-subjects design would provide the best results. A between-subjects design was eventually chosen so as to reduce learning effects.

Thirteen subjects took part in the experiment. Six (4 male and 2 female) tested the Fiesta while seven (4 male and 3 female) tested the Volvo. The subjects were all students, with a mean age of 22.9 and a range from 21 to 26 years. None suffered from any physical disability and none were informed of the nature of the study until the day of the test. Nationality was diverse, the subjects came from 6 nations. The subjects were asked to wear light clothing and most arrived for the tests dressed in trousers and light shirts. Twelve of the subjects wore light and flexible trainers or town shoes, while one wore heavy boots. Each subject performed one test with one of the two automobiles. The automobile was stationary in an open parking lot with the motor off. Each test took roughly 30 minutes to perform and consisted of the following phases:

Phase	Tasks Performed and Informations Obtained
Participation Form (~3 minutes)	The subject was asked to read the instructions describing the intended purpose and nature of the experiments and to sign a consent agreement to participate.
Driving Posture Adjustment (~4 minutes)	The subject was asked to adjust the seat and other systems and to attach the belts. The subject was then asked to simulate a driving task as realistically as possible, and to readjust all parameters as many times as necessary until a comfortable driving posture was reached which guaranteed good outside visibility.
Subject Data Form (~2 minutes)	The subject was asked to furnish several general informations such as age, physical disabilities, sports practised and interests. The subject was then measured in several anthropometric dimensions.
Measurement of Postural Angles (~4 minutes)	The body angles α, β and γ were measured in two positions: with the foot just contacting the clutch pedal (start of stroke) and with the pedal completely depressed (end of stroke).
Clutch Usage Task (8 minutes)	The subject was instructed to perform 8 minutes of pedal actuation at a fast fixed rhythm so as to induce some muscle fatigue. The subject was instructed to analyse the situation as carefully as possible.
Subjective Questionnaire (6-8 minutes)	The subject was asked to fill out the 3 part questionnaire (total of 4 pages) as carefully as possible.
Actuation Recording (1-2 minutes)	The subject was asked to run through the gears in the sequence 1-2-3-4-3-2-1. It was asked that the gear changes be vigorous as preliminary tests had shown that the force sensors were not accurate for very slow (low frequency) movements.

Table 1) Phases of the test procedure.

Results: Clutch Disengagement Forces

Figure 6 below presents the results from the static tests of the two cars.

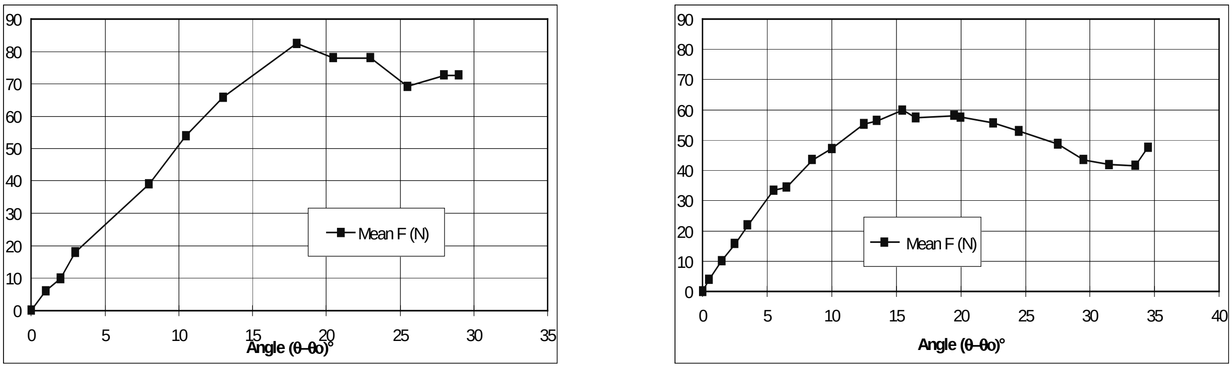


Figure 6) Static force-angle curves for the Ford (left) and the Volvo (right).

It can be seen that the Ford presented higher disengagement forces and used a smaller angular range than did the Volvo. While the differences in angular range were probably due to design, the force differences could simply reflect differences in clutch wear [9]. The static curves were measured in equilibrium, therefore they do not show the force build-up due to dry friction in the clutch system or the force at the end of the disengagement stroke due to the end-of-travel impact. Figure 7 presents an example of the dynamic pedal force and acceleration during disengagement.

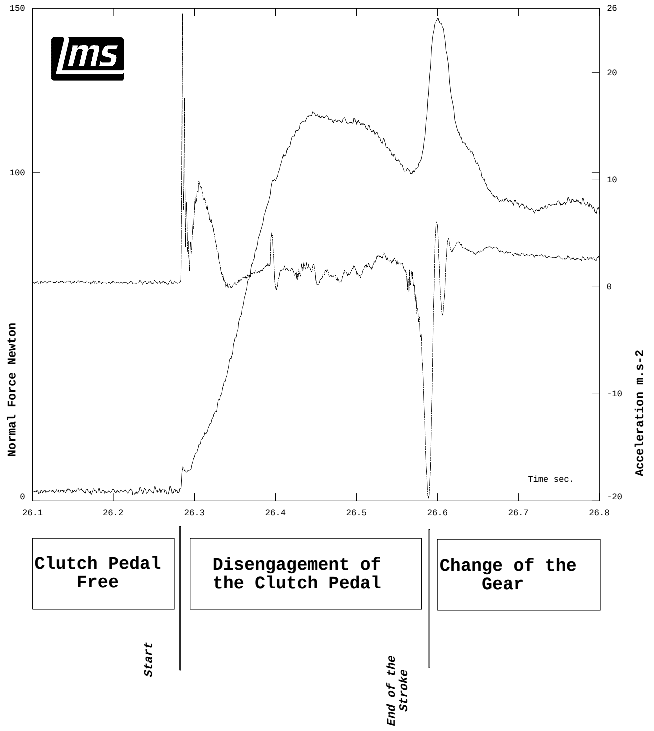


Figure 7) Typical force and acceleration time histories for clutch disengagement.

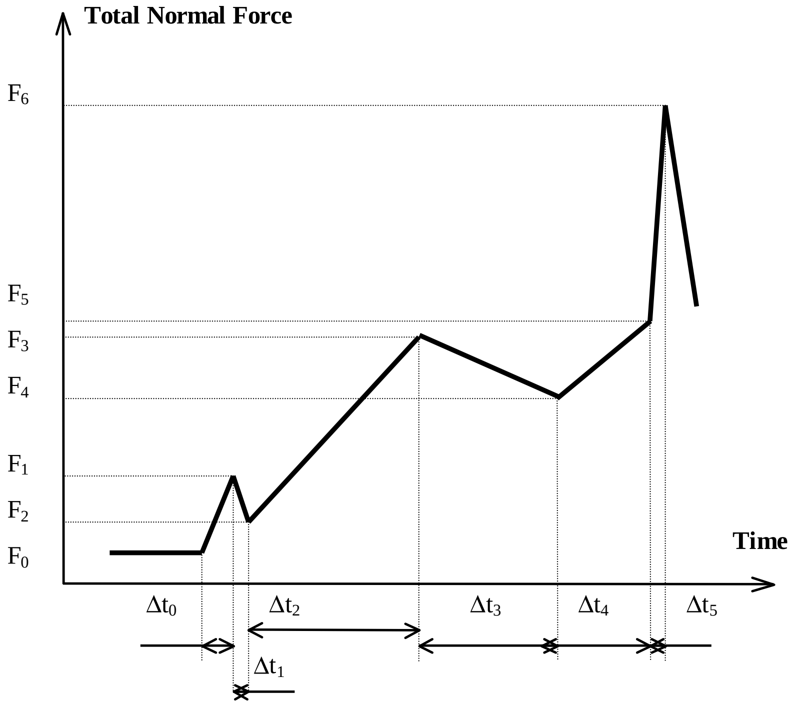


Figure 8) Clutch disengagement parametric curve model.

Figure 8 presents the simple clutch disengagement parametric curve model defined for the purposes of this study. The parametric curve model provides a simple summary of the salient features found in the force data of all subjects and is based on a series of fixed points:

1. The maximum break force due to dry friction in the clutch system.
2. The minimum force which occurs after pedal movement begins.
3. The maximum force before disengagement.
4. The minimum force after disengagement.
5. The force at the beginning of the end-of-travel impact.
6. The maximum force during the end-of-travel impact.

The values at all 6 points were read from the force time histories of all five tests of each subject. Besides the force values themselves, the time intervals between points and the average slopes from point to point were also recorded.

The force rise due to dry friction was found to be as high as 10 N in the case of the Ford, while the Volvo presented little evidence of dry friction. The end-of-travel impact was found to produce high forces in both cars. The mean value found across all tests of the two cars was 124 N with a standard deviation of 38 N. The maximum value recorded was 200 N. On average, the end-of-travel impact represented a 32% increase over the maximum force before disengagement (point 3).

The repeatability of the force time histories was found to be high for each subject if they were keeping to a fixed rhythm. Of the six forces of the clutch disengagement parametric curve model, the one which varied most across tests of the same subject (lowest repeatability) was the maximum force during the end-of-travel impact (point 6). The subject with the highest repeatability for the impact produced a mean value of 150 N and had a standard deviation of 10 N. The subject with the lowest produced a mean force value of 190 N and a standard deviation of 30 N.

The force curves were found to be quite different for the Ford Fiesta and the Volvo 340, with the Ford curves being generally higher. For example, the force at the point 3 before disengagement was found to be more that 25 % higher on the static curves and an average of 21 percent higher on the dynamic curves. The Ford also had a very strong force rise due to dry friction which was almost totally absent in the case of the Volvo, and the Ford also had the larger end-of-travel impact.

Results: Questionnaire Responses

The first question asked whether feelings of discomfort were experienced at any time when actuating the clutch pedal, 9 subjects responded yes while 4 responded no. The second question asked whether feelings of fatigue were experienced at any time when actuating the clutch pedal, in this case 10 responded yes while 3 responded no. These results suggest that the 8 minute clutch usage task managed to tire many subjects, thus bringing out strong subjective impressions.

The force differences between the two cars at all six disengagement model points were found to be higher than the Weber Fraction determined by Southall [19] for pedal force perception (7%). Therefore the human subjects would in practice be expected to perceive such force differences, and it might be expected that this would translate into differences between the two automobiles in the subjective questionnaire results. T-tests were calculated (11 degrees of freedom) for all questions of the subjective questionnaire. Statistically significant differences were found between the results of the two automobiles in the case of three questions:

- the body part discomfort rating for the lower leg region E $(p < .01)$
- the body part discomfort rating for the upper thigh region G $(p < .05)$
- the question “How much resistance did you encounter when pushing the clutch ?” $(p < .05)$

The Ford was rated more comfortable than the Volvo in the case of the lower leg (region E) while the opposite was true for the upper leg (region G). Interestingly, the Volvo was rated as having the highest pedal resistance even though the force curves were generally lower.

The final three questions asked whether the presence of the pedal transducer interfered with the subject’s natural movement and comfort. A 10 point scale similar to that of Figure 4 was used with “not at all” being assigned a value of 1 and “very strongly” a value of 10. The average values and standard deviations were 2.54 (σ=1.27), 1.85 (σ=1.14) and 2.23 (σ=1.36) suggesting that the presence of the transducer should have had only a minimal effect on the clutch actuation task.

Results: Correlation Analysis

A general correlation analysis was performed by calculating Pearson r coefficients [5,8] between all possible pairings of mechanical versus subjective values, and between all possible pairings of postural versus subjective values. The objective was to identify the quantities which most affected human perception of comfort during clutch disengagement. Force values, slope values, time values, postural angle values and questionnaire results were assembled and correlated.

Since 13 subjects were used and 2 variables were correlated each time, the number of statistical degrees of freedom was 11. For 11 degrees of freedom any r value in excess of r=0.553 is to be considered significant at a 95 percent confidence level [8]. Nine data pairings produced a Pearson r coefficient higher than r=0.553. The mechanical and postural parameters involved were:

- the change in the thigh-trunk angle $\Delta\alpha = \alpha_2 - \alpha_1$
- the maximum end-of-travel impact force at point 6
- the slope from point 5 to 6 during end-of-travel impact
- the slope between points 2 and 3 before disengagement

Figure 9 presents the data, the fitted regression lines, and the portion of the variance accounted for (r^2) for the nine data pairs. The highest Pearson r coefficients were found between the change in trunk-thigh angle ($\Delta\alpha = \alpha_2 - \alpha_1$) and four of the general subjective responses. $\Delta\alpha$ accounted for more than 60 percent of the variance for two of the questionnaire responses. For all questionnaire responses the level of comfort increased as $\Delta\alpha$ increased. Significant correlations were also found for the end-of-travel impact force, the end-of-travel impact slope and the slope of the force curve before disengagement (from points 2 to 3). While these correlations were weaker, the size of the effect was actually greater in several cases such as the end of travel impact force and slope. It was interesting to find that comfort actually rose with rising force or slope in several cases.

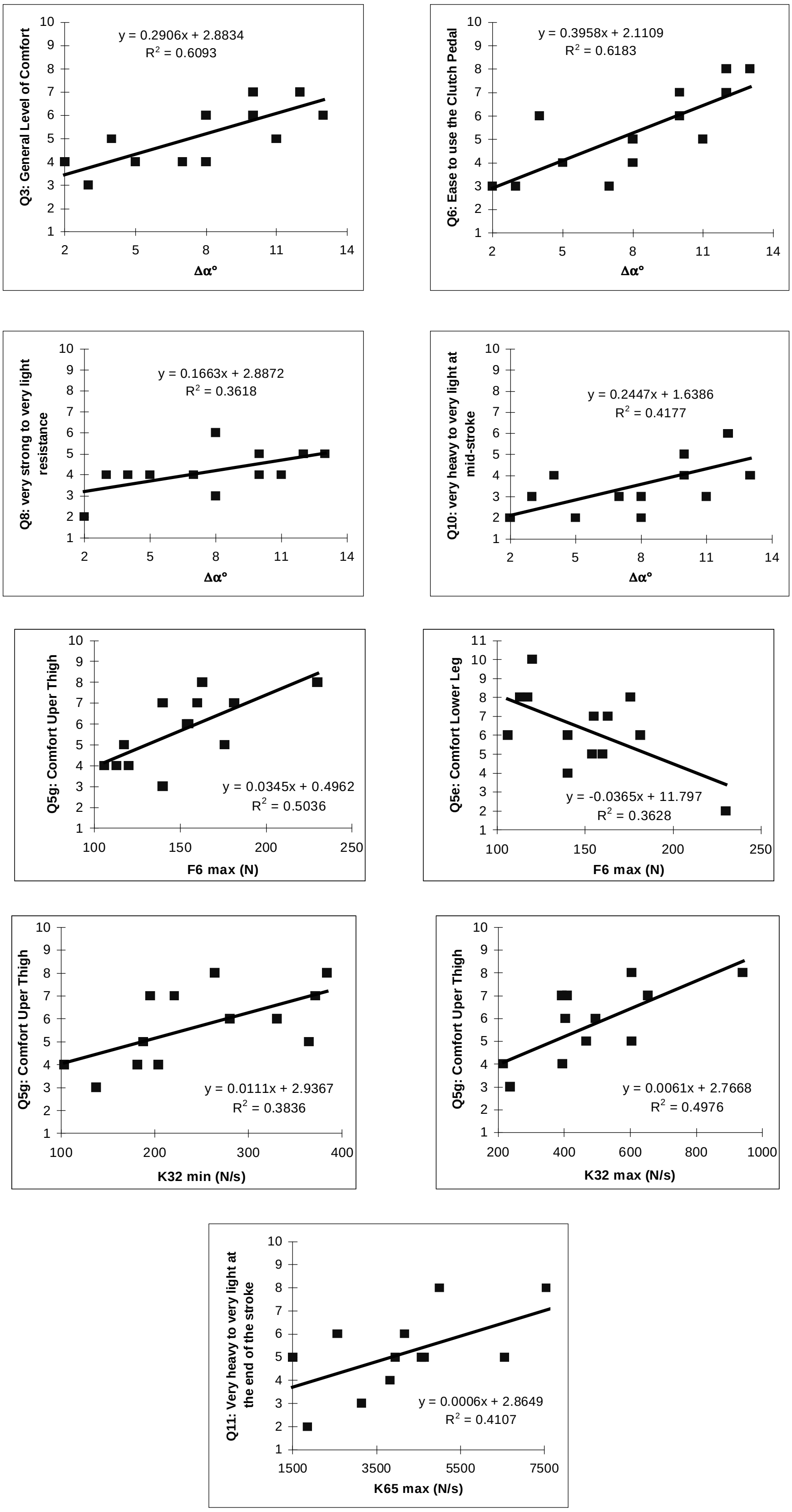


Figure 9) Data pairings which produced significant correlations.

Discussion

One observation is that the static and dynamic force curves were pretty much the same except for the initial rise due to friction and the end-of-travel impact. This is a confirmation of the low frequency nature of voluntary human movement. Hutchinson et. al. [7] compared joint forces and torques calculated by inverse dynamics for an 11 segment model of the human body when rising from a chair. Their objective was to determine whether dynamic forces needed to be calculated when analysing human motion for simple tasks or whether traditional quasi-static methods [1] were sufficient. Their data, averaged for 10 subjects, showed that dynamic forces and torques accounted for less than 1% of the total at the ankle and knee, less than 10% at hip, and just over 15% at the back and neck. It was concluded that quasi-static methods were sufficient for calculations involving the lower body. Similar results are found in the gait analysis literature. One paper by Angeloni et. al. [2] states that "the frequency content of normal gait is generally considered to lie within a narrow band, with the upper limit between 4 and 6 Hz". They also state that "Fourier coefficient reconstruction of displacement data is generally done using the number of coefficients corresponding to a frequency content of less that 15 Hz". They go on to make a distinction between foot kinematic data and force plate data by stating that "force plate data have been shown to have a broader spectrum, between 15 and 75 Hz". The results of this study suggest that when the foot encountered only the relatively low resistance of the clutch spring, the movement was voluntary in nature hence low in frequency. When the pedal reached end-of-travel, the resistance changed too rapidly for voluntary action, hence the dynamics approximated that of a passive impact with a velocity initial condition. The impact caused high forces extending to high frequencies. While this paper does not discuss the analysis performed on the acceleration data, it is sufficient to state that good resolution of the end-of-travel impact required sampling rates in the range from 500 to 1000 Hz. In future studies it may be useful to split the analysis task into two problems or phases, a low frequency voluntary motion phase and a high frequency impact phase.

A second observation is that the body part questionnaire furnished statistically significant results for highly localised body regions. The lower leg region E and the upper thigh region G isolated specific muscle groups which were found to fatigue quickly with pedal actuation. Targeting these specific muscle groups in future studies would be expected to be beneficial.

The main result of this study is that several mechanical and postural parameters provided significant correlation values. The change in trunk-thigh angle ($\Delta\alpha$), the slope of the force curve before disengagement, the maximum end-of-travel impact force and the slope during impact, were all found to be correlated with comfort. The variety of parameters identified suggests the multifactorial nature of human comfort when actuating pedals. The results suggest that a "clutch meter" will have to measure several postural and force quantities starting with those identified in the current study.

Another observation is that the correlation between the trunk-thigh angle $\Delta\alpha$ and subjective comfort supports the suggestion made by Haslegrave [6] that "the clutch can be heavier if operated by a thrusting action using the strength of the leg muscles rather than the weaker muscles acting around the ankle joint". Comfort improved as $\Delta\alpha$ increased. A vehicle or simply a seat which limits thigh movement may require the driver to transfer effort to the lower leg thus increasing the discomfort.

A final comment is that the tangential pedal forces were not measured in this study. Anecdotal evidence suggests that these forces play a role in determining clutch actuation comfort, therefore they should be evaluated in future studies.

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