Towards the integrated measurement of hand and object interaction

TOWARDS THE INTEGRATED MEASUREMENT OF HAND AND OBJECT INTERACTION

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Abstract

This paper describes the first stages towards an integrated package of quantitative methods for the measurement of hand-object interaction. To date, quantitative data concerning a product's ease of use has not been adequately defined to assist product developers and legislators in their evaluation. A better understanding is needed of the complex interaction between the hand and an object during task performance

A model of the physical interaction between hand and object is described that emphasises the role of the biomaterials of the hand rather than focusing on the conscious implementation of muscle involvement. The model subdivides hand-object interaction during grip into three levels: Gross interaction where the skeletal structure and muscles influence the grip pattern providing a mechanical structure to clamp the object; Intermediate interaction, where the soft tissues of the palm of the hand provide a mechanical interlock with the surface features of an object; and Micro interaction, which involves adhesion between the sebum, epidermis and surface material of the object.

This model of hand-object interaction provides a contextual framework for the measurement of levels of hand-object interaction. A battery of methods, which includes consideration of anthropometry, joint range of movement, grip strength, finger compliance, finger friction and the measurement of dynamic task performance, is described. A case study is used to illustrate the potential application of such data for the design/redesign of a product.

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Introduction

Within modern society there are many tasks (work and leisure) which require a person to use their hands at the limits of their capabilities i.e. involve prolonged static grip and manipulation. In these instances it is particularly important to improve hand-object interaction to achieve optimum efficiency, safety and wellbeing.

Hand-object interaction is the primarily static connection (grip) between the hand and an object formed for the purpose of performance of a task. A lack of standards and guidelines in the area of hand-object-interaction make it difficult for the professionals involved in product design, for example designers, manufacturers and ergonomists, to justify their decision making. A criticism of current methods of hand assessment such as grip strength, joint range of movement and timed dexterity tests is that they do not adequately explain the ability to perform tasks. In fact, grip strength rapidly declines during task performance.

Blair (1999) cites the following as being important in the accurate assessment of hand performance: methods should be tested for reliability and repeatability; they should be sensitive to changes in performance; tests should permit quantification, and data collection procedures should be standardised. The authors of this paper also consider these criteria important.

An understanding of static grip is essential to start to improve product design and to improve the users' perception of comfort and ease of use. If an object slips within the hand, grip increases until stoppage occurs: a user may perceive this as loss of control, which may have safety implications. Conversely, a user will reduce their applied grip force until the object reaches a point just before slippage occurs (Edin et al, 1992). It has been noted that injuries to tendons may be as a result of excessive grip forces to prevent slippage (Cochran and Riley, 1986). A product that enables static grip to be produced requiring a minimum of grip strength to maintain it will be perceived as being easy to use. In order to optimise static grip performance a better understanding is needed of the biomechanical characteristics of the hand and how the biomaterials within it interact with an object. A model was developed by the authors (Torrens 1997) which defines grip as three levels of interaction:

1. *Gross interaction.* This involves the skeletal structure and muscles and relies on grip patterns, posture, mobility and strength. It provides the mechanical structure to clamp the shape of an object.
2. *Intermediate interaction.* This is where the soft tissues of the glaborous (hairless) surface of the palm of the hand mechanically interlock with the large surface features of an object.
3. *Micro interaction.* This is where the skin surface interacts with the fine surface material of the object. This interaction is primarily a form of adhesion and is a combination of sweat (sebum) and the dead skin layer (epidermis).

Factors, which have been shown in the literature to influence grip strength, regardless of the instrument or technique used, are summarised in Table 1. Humidity, ambient temperature and other external factors may also affect the characteristics of the biomaterials of the hand. In addition, physiological factors, such as exercise, and psychological factors such as emotional stress, both leading to palmar perspiration can also influence measurements taken as sweat may decrease friction properties changing the mechanical characteristics of the skin.

The aim of the research is to develop methods to measure aspects of hand-object interaction and so lead to a better understanding of the complex interaction between the hand and an object during task performance. In addition, data are being collected on healthy adults (n=100) in an attempt to start to produce normative data including grip strength, finger compliance and finger friction. It is hoped that this will lead to improved interaction with products and so increased safety, comfort and performance. This paper will describe the development of an integrated package of quantitative methods to measure hand-object interaction. A case study is presented illustrating the application of such data to designing.

Table 1. A summary of factors which influence grip strength

Factor	
Sex	Grip in males is significantly stronger than in females - n=120 (Fraser and Benten, 1983)
	Females are more dextrous than males - n=252 (Kellor et al, 1971)
Age	Positive correlation between age and grip strength up to 30 years, then a deterioration with age, especially after 50 years - n=960 (Balogan et al, 1991a)
Height and weight	Positive correlations for height and weight with grip strength - n=960 (Balogan et al, 1991a)
Hand dominance	No significant difference in grip strength between right and left hand - n=120 (Fraser and Benten, 1983)
	Dominant hand is 13% stronger (Lunde et al, 1972)
Occupation	Stronger grip with non-dominant hand due to stabilising objects with this hand whilst performing fine motor tasks with dominant hand - n=22 (Fraser and Benten, 1983)
Motivation	Level of motivation affects the maximal effort - (Somadeepti, 1990 - n=60; Chi and Drury, 1988 - n=11)
Physical impairment	Conditions such as rheumatoid arthritis influence grip strength. Within subjects this may vary day to day and hour to hour.
Posture	Grip strength is greater in standing than in sitting - n=9543 (Teraoka, 1979)
	Grip strength increases from elbow flexion to extension - n=61 (Balogan et al, 1991b)
	Grip strength is stronger with the elbow in a 90° flexed position compared with a fully extended position - n=29 (Mathiowetz, 1985)
	Grip strength is lower when the wrist is in 15° of flexion - n=30 (Pryce, 1980)
Other factors	Warm-up prior to testing leads to increased maximal grip strength - n=30 (Marion and Niebuhr, 1992)

Method

The model of hand-object interaction (gross interaction, intermediate interaction and micro interaction) provides a contextual framework for the measurement of levels of hand-object interaction (Table 2). Data collection has commenced using these methods, which are now described. It is also planned to collect other data, for example pinch grip and skin moisture.

Subject and room preparation

The experimental room is air-conditioned and controlled for ambient temperature (i.e. 22-24 °C). Efforts are made i.e. keeping windows and doors closed, to keep the room free from airborne contaminants, which may affect the finger friction and compliance measurements.

All of the measurements require standard procedures for reliability and repeatability, which are documented for the experimenter. For example, posture is standardised for the anthropometric measurements, grip strength, finger compliance, finger friction measures; and the instruments are calibrated as required prior to data collection. Skin temperature is monitored and controlled to allow more accurate comparisons between subjects for the finger compliance and finger friction data.

Table 2. Hand-object interaction and related test methods

	Equipment	Measures
Gross interaction	CODA motion analysis; goniometer; video recorder; anthropometer.	Dynamic movement analysis (x, y and z co-ordinates related to time); wrist joint range of movement (°); observation of posture and grip patterns related to the task; anthropometric measurements (mm).
Intermediate interaction	Universal grip dynamometer; finger compliance meter; Grip dynamometer (Baseline); thermocouple.	Measurement of the forces through the hand related to a task (x, y and z axes related to time); finger compliance (vertical displacement - mm; and horizontal displacement; mm^2); grip strength (Kg); surface skin temperature - finger (°C).
Micro interaction	Friction meter; thermocouple.	Finger friction (coefficient of friction); surface skin temperature - finger (°C);

Anthropometry
Anthropometric measurements are taken i.e. height and weight; for the right hand (finger-tip arm length, finger-tip wrist length, hand breadth) and right index finger (finger-tip length, finger tip width, finger-tip depth) and compared with population norms for the UK (Peoplesize, 1996). Procedures were based on those described by the British Standards Institute (1990).

Range of movement (goniometer)
The position of the wrist is well documented as having an influence on grip strength, therefore the focus of these measurements is on maximal wrist joint range i.e. wrist flexion and extension; and radial and ulnar deviation of the wrist. These are measured using a simple goniometer.

Dynamic motion analysis
Pilot trials are also taking place using the CODA 3D motion analysis system to enable the 'real time' recording of joint range during a particular task. The system uses markers made up of a light emitting diode (LED). Detectors consisting of three angular resolution solid-state sensors track the active LED markers sequentially. The markers are triggered sequentially by an infrared emitter on the CODA machine. The resolution of the CODA is much higher than conventional video cameras (1 in 60,000).

Observation
Performance of the task based on interaction with the Universal Grip Dynamometer (in conjunction with the CODA motion analysis system) is videotaped for observation of posture and grip patterns. Video recording is used specifically to identify the grip patterns used at a particular moment of time during the task.

Universal grip dynamometer (UGD)
This device was developed at Loughborough University and enables the measurement of forces acting through an object i.e. a handle, by incorporating the handle within its framework. It measures both linear and torque forces in six degrees of freedom. The test handle is placed within the dynamometer, between brackets that are force sensors. The strain gauge configuration is such that it enables the handle to be held in the brackets without creating internal stresses and so avoiding the need to recalibrate. The dynamometer brackets can then be attached to the equipment with the handle in the

same orientation as in the real product. The data are logged onto a spreadsheet for ease of processing. Differences in mass and distribution due to the weight of the instrument are considered during analysis of the results. Changes in force vectors, when they occur and the direction of slip during performance of a task help identify areas for consideration during redesign for optimum performance.

Monitoring the forces acting through the hand with the UGD, together with the video and CODA motion data will enable changes in grip and overall posture to be identified. Slippage (which may take place in several planes) indicates that the forces acting on the hand, at that moment within the task, have exceeded the hands grip performance. Slippage will be sensed as a loss of control and increasing muscle involvement to overcome the problem. The user may perceive the product as difficult to use.

Finger compliance

Vertical and horizontal compliance of the right hand index finger is recorded. Briefly, the subjects' index finger is inked and then placed under the top platen of the meter. A sheet of copy grade paper is then slid under their finger onto the bottom platen. The top platen is then pushed towards the bottom platter so that the finger is sandwiched between the two plates. A cyclic procedure then commences whereby the top platen squashes the finger onto the lower platen, taking around six seconds dependent on the size and compliance of the finger. Measurement of vertical displacement starts at 2N of applied force and ends at 10N. A mechanical clutch prevents the platens moving together when the force applied exceeds 20N. Subjects can reverse the travel of the moving platen at any time by using a panic button in their free hand. Horizontal displacement is calculated from the fingerprint area. This involves enlarging the fingerprint by 200% and then following the outline of the area with a planimeter stylus. The planimeter automatically calculates the area within the traced outline. There is a degree of operator error and therefore computer calculation of the image generated is being investigated.

Grip strength

There are many instruments commercially available for the assessment of grip strength. In this study the Baseline grip dynamometer was used which has a peak indicator, to record the maximal value in kilograms or Kg, (x 9.81 for Newtons N). As well as grip providing an indication strength and endurance during a task, grip strength may also give an indication of the characteristics of the skin and soft tissues of the hand i.e. the larger the muscle bulk the more likely the subject is to have thicker soft tissue and skin. The procedure followed is similar to that described by Bucholtz et al (1988). The dynamometer handle is set to 50mm and starting with their hands by their side, subjects are given the instrument and asked to grip the handle as hard as then can whilst bringing their hand and forearm up to a right angle with their upper arm. No encouragement is given to the subject by the researcher.

Finger friction

The measurement of finger friction has been developed and refined over a number of years (Bucholtz et al, 1988; Bobjer et al, 1993; Torrens 1996 and 1997). The finger friction meter consists of two calibrated strain gauges that produce a signal, which is then data logged and converted to a digital value (in Newtons). Normal i.e. downward force and frictional i.e. drag force are then calculated. Frictional force is displayed as a coefficient of static friction (normal/frictional force). Detail regarding the measurement of finger friction is described in a previous paper of the authors (Torrens 1996). Briefly, from a standardised position, subjects are asked to lightly rest the index finger of their right hand onto the test platen of the finger friction meter. The platen is 25mm x 25mm and the asperity or surface detail of the platen is 5mm wide and 5mm deep at intervals of 10mm. Earlier research has indicated that the optimum interval (or pitch) between each surface detail (or asperity) for optimal frictional qualities is, for both males and females 10mm. Subjects are then asked to press down their finger until they can bring a pointer in line with a fixed line on the indicator and to slowly draw their finger back towards their body whilst maintaining the position of the pointer.

Subjective data
Textures with wider grooves are associated with increased reported discomfort, but the continuation of narrower grooves and a large contact area is comfortable (Bobjer, 1993). Subjective data (a questionnaire and comfort/discomfort scales) will be used during recording of the task with the UCD.

Case study

The research team is developing a database of adults (n=100) for the objective measures taken such as anthropometric measures, grip strength, finger compliance and finger friction in an attempt to start to produce normative data. The collection of conventional measurements, such as anthropometric and grip strength data, enables these new measurements to be linked to existing data sets.

A case study (subject details in Table 3) is presented to illustrate how data from this research might be applied to a designing situation - in this case, the task of ironing. Design decisions are considered under the headings of the three levels of interaction for grip. It is the view of the authors that a hand held product which optimises grip (at all levels), according the needs of the task, will be easier to use. A design decision, which maximises performance at one point in time may compromise performance at another, and therefore, repetition of the process at important moments throughout the task is essential.

Table 3. Case study subject details (healthy male, 20 years old)

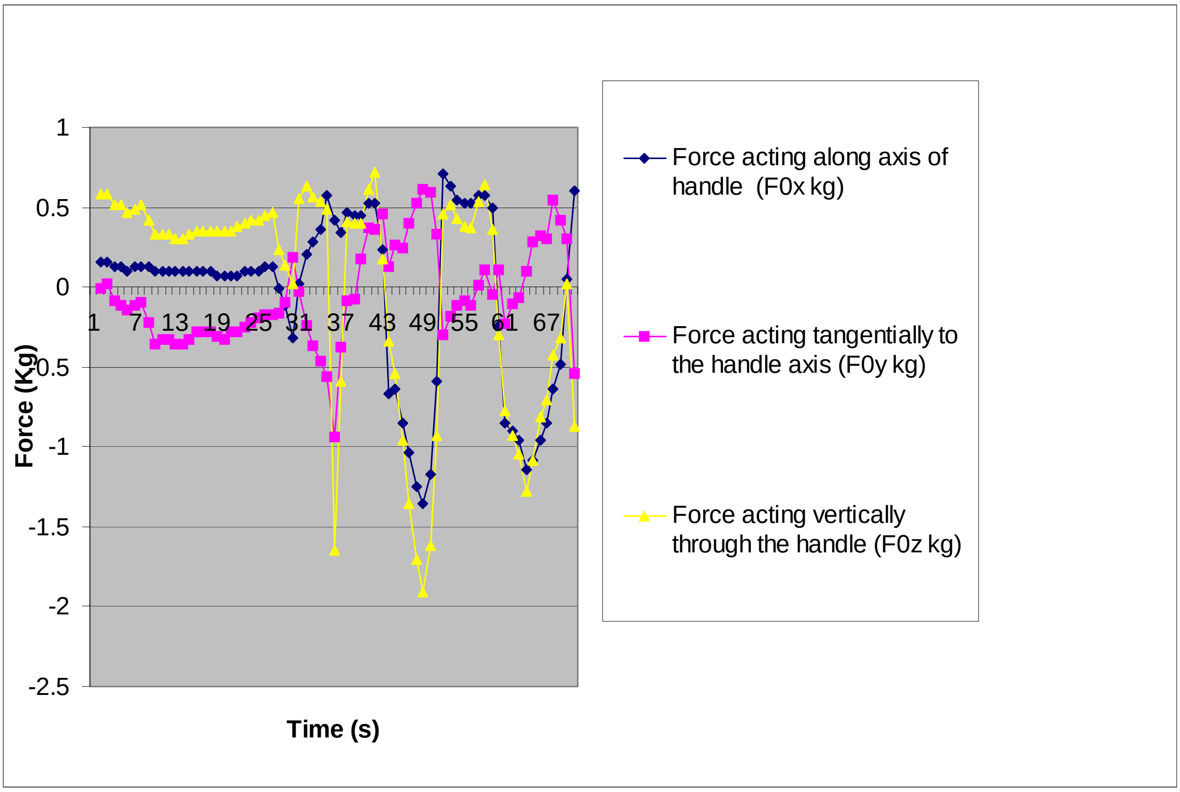
	Value (percentile)		**Value**
Height - mm	1874 (97^{th})	Grip strength	180 N
Weight - Kg	81 (72^{nd})		
Finger-tip arm length - mm	506 (93^{rd})	Wrist flexion	41°
Finger-tip wrist length - mm	199 (76^{th})	Wrist extension	60°
Hand breadth - mm	91 (72^{nd})	Ulnar deviation	32°
Finger-tip length - mm	30.44	Radial deviation	20°
Finger tip width - mm	18.09 (50^{th})		
Finger-tip depth - mm	17.38 (99^{th})		
Finger compliance		*Finger friction*	
Vertical displacement - mm	3.44	Coefficient of friction	1.7
Horizontal displacement - mm^2	40		

Gross interaction
Due to the complexity of hand-object interaction, a description of the interaction would normally be based on a selected moment in time during the ironing task. User evaluation will also help identify these key moments in task performance that require further investigation. Interview or focus group data enables the researcher to obtain qualitative opinions of ease of use and discomfort when using an iron.

Figure 1 shows the linear forces acting through the handle over a sample time of just over a minute at a sampling rate of 60 hertz. The three axes of forces are positive and negative, describing six degrees of freedom. What is interesting is that the downward (F0z minus) force and the force acting behind, resulting from the pulling action of the iron (F0x minus) have similar peaks at -1.3Kg and -1.9Kg. This indicates that it may be difficult to lift the iron off the piece of clothing and pull or drag the iron back across it. The weight of the Universal Grip Dynamometer (UGD) combined with the iron's base plate is nearly three times the weight (at 4.95 Kg) of a conventional iron (1.3 Kg) accounting for the large lift force required. This force would not be required using a conventional iron and therefore should be disregarded.

Anthropometric data are used for decisions regarding optimal handle length, which will affect the grip pattern. The aim is to achieve maximal mechanical interlock of the hand, but to avoid involving maximum grip strength. Reviewing the grip pattern and posture of the subject, from data recorded on video and using the CODA system, there are a number of points to be addressed within the gross level of interaction. The grip pattern for the task (ironing) was largely power grip as defined by Napier (1956). A return on the handle at the front of the iron, or a widening of its shape, provides a mechanical stop against which the thumb and index finger can press. This will reduce the shear forces acting through the power grip on the skin and underlying tissue of the hand, reducing the need for prehensile grip.

Figure 1. Linear forces acting on the handle during an ironing task



The use of a power grip indicates the use of the larger muscles of the forearm rather than intrinsic muscles within the hand and that the subject could repeat the task for some time. The angles between the hand and forearm are close to neutral with the hand in pronation (palm down), so aiding efficient use of arm muscles in maintaining grip. Reviewing the CODA recording it can be seen that the upper arm and torso move together during the ironing task. This indicates that the arm and grip posture of the subject is unlikely to change over the time taken to iron a garment. This may be of concern if the subject is involved in commercial clothes ironing as exposure of the shoulder, elbow and wrist joints to repeated loading in the same position could cause longer-term injury. Repositioning of the ironing board height or offering a handle, which allows a number of possibilities for changes in grip position, will enable slight changes in posture and joint position.

The peak force (1.3Kg/13N) during the drag or pulling action of ironing suggests that the shape of the flat edge of the back plate of the iron may need consideration. It should also be noted that the extra weight of the instrumented iron (UCD) increases the inherent downward force. The amount of downward pressure required using a conventional iron would be a combination of current downward force (1.3Kg/13N) plus around 3Kg of extra weight from the UDG, total 4.3Kg/ 42N. The relatively large downward force required would suggest the use of a broad handle cross-section, i.e. wider than it is thick, based upon anthropometric proportions of the target user. A broad handle will help distribute the pressure over the contact interface between hand and iron. Contact pressure should be distributed around the knuckles (metacarpophalangeal joints or MCPs) and thumb (thenar) pad avoiding pressure on sensitive areas of the hand and wrist, through which tendons, nerves and blood vessels pass. To achieve this, the handle shape should consist of flat planes with a minimum of convex curvature along the axis of the handle (x axis). The cross-section of the handle should be organic in profile to avoid high pressure points at intersections of flat planes. Side forces in the Y plane (F0y) were comparatively low, (below +/- 1Kg).

Intermediate interaction

Analysis of the forces acting through the handle suggests that it is the downward and forward forces that the product developer should prioritise for optimisation of grip. Earlier pilot research has shown that intermediate interaction is best optimised when the forces are over 2Kg/20N. In this case low forces (under 2Kg/20N) are involved and therefore are most effectively optimised through gross and micro levels of hand object interaction. Using highly featured surfaces that interact at the intermediate level of grip will cause discomfort due to the creation of high pressure points on the hand, relative to the rest of the handle. Surface details such as ridges, or dimples, that are spaced at intervals of 10mm the (optimum interval or pitch, Torrens 1996 and 1997) and less than 3mm in depth or height for grip are suggested (subject compliance 3.44mm). From pilot work of the author, it is recommended that for people with weak grip and limited dexterity, the surface features should be less than 2mm in depth or height to avoid a feeling of discomfort. A reason for this is that skin quality may be poor and less capable of supporting differences in pressure.

Micro interaction

Research has suggested that a surface should have fine features, as well as the larger features for optimum grip. It is recommended that these fine surface features be less than 0.5 mm in height are in the form of a surface texture e.g. a sand blasted finish. Micro interaction is usually optimised using an elastomer material, with rubber-like qualities such as neoprene. These high friction materials may be used at points where a higher force is produced as indicated by the UCD or where slippage takes place (UCD and CODA measurements). Optimising grip may affect comfort: Materials with low frictional properties i.e. soft and smooth to touch, as on the handle of an iron (which may be preferred), generally lack the feeling of 'control'. Patches of rubberised material at points of slippage identified on the handle may be one design solution. For people with weak hands, high friction materials may enable them to perform a task, which would otherwise be impossible. Low friction may be preferable for a task when the hand needs to frequently change position and slide over the surface. Also if the iron were to be used in an environment where there were contaminants e.g. sweat, intermediate interaction would need to be prioritised as contaminants reduce the effect of micro interaction, leaving intermediate and gross interaction to maintain grip.

Summary of recommendations for iron design

The following are suggestions relating to a target market comprising of young males, 18-22 years old, in the UK:

- The handle should be 100 mm or more in length and have clearance on the underside of the handle of greater than 35 mm.
- The cross-section of the handle should be between approximately 20 mm wide and 15 mm thick (based on proportions and anthropometric data).
- The handle should have a large end stop located at the front and rear of the handle.
- The handle should have a sand blasted texture finish, with no large surface features or ridges.
- A rubberised material such as Evoprene ‘G’ should be used at points of slippage on the handle.
- A review of the iron's base shape and overall weight should be undertaken to define optimums for ease of use.
- A review of the alternative handle positions should be undertaken to define optimums for ease of use for short and longer periods of ironing.
- Guidelines should be given with the iron to enable the height for ironing to be optimised for the user.

Concluding remarks

This paper has briefly outlined some of the methods being developed to measure hand-object interaction. Our aims for future research in this area are:

- To continue to develop standardised methods for the measurement of hand-object interaction.
- To produce a normative database of the adult population of the UK with details such as hand anthropometry, wrist joint ranges of movement, finger friction, finger compliance and grip strength.
- To enable the prediction of the hand performance of a selected 'population' e.g. females over 70, whilst interacting with a specified product / product type (e.g. irons).

It is expected that the detailed measurement of hand characteristics and performance will enable professionals involved in product design to make more informed decisions regarding design specification.

Another application of the research is in the area of hand-glove-object interaction. This is important for individuals involved in hazardous environments such as deep sea diving or the nuclear industry where protective equipment reduces sensory perception, mobility and often the available muscle strength. Gloves are not well attached to the hand, leading to shear between the hand and glove; and the glove and object. Research is being conducted to improve connection between the glove and the hand.

Acknowledgements

The authors would like to thank the Defence Clothing and Textiles Agency for their support with this research.

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