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Variables influencing the frictional behaviour of in vivo human skin

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0 ABSTRACT

In the past decades, skin friction research has focused on determining which variables are important to affect the frictional behaviour of in vivo human skin. Until now, there is still limited knowledge on these variables.

This study has used a large dataset to identify the effect of variables on the human skin, subject characteristics and environmental conditions on skin friction. The data are obtained on 50 subjects (34 male, 16 female). Friction measurements represent the friction between in vivo human skin and an aluminium sample, assessed on three anatomical locations.

The coefficient of friction increased significantly ($p < 0.05$) with increasing age, increasing ambient temperature and increasing relative air humidity. A significant inversely proportional relationship was found between friction and both the amount of hair present on the skin and the height of the subject. Other outcome variables in this study were the hydration of the skin and the skin temperature.

1 INTRODUCTION

For over 60 years, researchers in a diversity of domains have studied the frictional behaviour of the human skin, in order to determine which are the important influential variables. These domains include mechanical engineering, material science, product design, dermatology and rehabilitation. Limited knowledge is available on the influence of the various parameters on the frictional behaviour of the skin and little is known about the mechanisms by which skin friction is influenced. Possible reasons for the limited knowledge can be found in the large interpersonal variation in combination with the fact that most conclusions are based on only a limited number of subjects.

Skin friction is a system parameter which depends on the characteristics of both the human skin and the material in interaction with the skin, as well as on the environment surrounding the materials and the contact parameters. The material in contact with the skin is often an engineering material and can be described unambiguously with parameters commonly used in materials engineering (including type of material and surface roughness). It is by contrast more complex to describe the characteristics of the skin. In vivo human skin has been associated with a large number of influential variables, of which age (Arumugam et al., 1994; Asserin et al., 2000; Childs and Henson, 2007; Edwards and Marks, 1995; Fagiani et al., 2011; Flynn et al., 2011; Gross et al., 1992; James et al., 1994; Kvistedal and Nielsen, 2007; Lewis et al., 2000; De Morree, 2000; Widmaier et al., 2006; Wilmore and Costill, 2004; Zahouani et al., 2011; Zhu et al., 2011), eating and drinking habits (James et al., 1994; De Morree, 2000; Rawlings, 2006; Widmaier et al., 2006; Wilmore and Costill, 2004) and time of year (Madison, 2003; De Morree, 2000; Rawlings, 2006; Widmaier et al., 2006; Wilmore and Costill, 2004) are merely examples.

Knowledge of skin friction can be used to prevent injuries and discomfort at the human skin. One of the main purposes of skin friction research is to prevent injuries and complaints of the skin. These injuries can be caused indirectly by falling or slipping of objects, or directly by excessive shear forces, which can lead to blisters, ulcers, lacerations and skin irritation. Another objective concerns treating the symptoms of skin damage and to limit the complaints. This can be achieved by treating the symptoms of skin injuries or complaints concerning the skin: for example applying hydrating creams in case of xerosis or psoriasis (Anderson, 1981; Brody, 1962; De Morree, 2000).

The situations in which skin friction is important, have been associated with a large variation in skin characteristics, material properties and environmental conditions. In order to select the suitable conditions for a skin friction application of interest, the following three items are of main concern:

(1) Which parameters influence the friction in skin-object contact?

(2) How does a change in this parameter influence the frictional behaviour?

(3) What is the extent of this effect?

Researchers with an engineering background often express the skin's properties in terms such as skin layer thickness, Young's modulus and shear strength. In fields like product development, alternative indicators may give more insight. For example, it may be more comprehensive to relate the development of friction blisters to gender rather than to the shear strength of the granular layer of the epidermis. In fact, numerous variables have been associated with skin friction and even more variables have been reported in the literature to influence the skin's properties.

The objective in this paper is the identification of variables that influence the tribological behaviour involving the human skin. The results are based on a large dataset, measured between the skin and aluminium, at a constant load of 1.2N and constant velocity of 10 mm/s on three locations on the left upper extremity: the middle of the ventral aspect of the forearm, the middle of the dorsal forearm and the palmar aspect of the distal phalanx of the index finger, also referred to as index finger pad.

2 METHODS

For all subjects, a strict protocol was followed for the execution of the measurements. First the subject is given information about the study, the objective and the measurements, followed by providing informed consent. The subjects completed a questionnaire, followed by the measurements of the skin hydration and skin temperature on all assessed anatomical locations. The skin friction measurement were executed successively.

2.1 Questionnaire

In this study, the effect of potentially influential variables on the frictional behaviour is assessed. In order to obtain information on personal variables and characteristics, the participants completed a single questionnaire.

The variables for the questionnaire were extracted from literature after advice from experts on skin. This set of variables was expanded based on discussions with random people from the street, who were asked which variables they thought would influence either the skin's properties or the friction involving the human skin. This procedure was followed to prevent the accidental omission of variables based on experts opinions and/or previous research findings. The variables that these people mentioned corresponded to the variables in the literature. A questionnaire was built from the variables. With the design of the questionnaire it was kept in mind that any literate person, independent of their background or their educational level, could answer the questions without requiring any help of the researcher.

In the introduction of the questionnaire, participants were informed about the purpose of the study. The questionnaire contained both closed and open ended items. As a pre-study the questionnaire was presented to a group of 15 people in different backgrounds, professional disciplines and educational levels. The objective of the pre-test was to assess whether the questions were unambiguous, easy to answer and whether the questionnaire was not too long. All volunteers indicated that the provided information as well as the questions were clear and easy to understand. The questionnaire could be answered within two minutes without further explanation or elucidation.

Based on the comments of the volunteers, the questionnaire was refined. The variables in the final questionnaire are listed in Table 1. Additionally, the body mass index (BMI), defined as the ratio of the body mass over the height squared: $BMI = BodyMass / (Height)^2$, was calculated for each participant

The researcher noted down additional variables for each subject and six variables were measured for each measurement condition: the static and dynamic coefficient of friction, skin hydration, skin temperature, ambient temperature and air humidity. In the literature, the type of material of the contact (Adams et al., 2007; Asserin et al., 2000; Bertaux et al., 2010; Bobjer et al., 1993; Derler et al., 2012; Elleuch et al., 2007; Gerhardt et al., 2008a; Lewis et al., 2000; Sivamani et al., 2003; Tomlinson et al., 2011; Zhang and Mak, 1999), the normal load between this material and the skin (Adams et al., 2007; Bobjer et al., 1993; El-Shimi, 1977; Elleuch et al., 2007; Gerhardt et al., 2008a; Gitis and Sivamani, 2004; Koudine et al., 2000; Skedung et al., 2011; Zhang and Mak, 1999), and the relative velocity between the materials (Bobjer et al., 1993; Bullinger et al., 1979; Elleuch et al., 2007; Gerhardt et al., 2008a; Zhang and Mak, 1999) are considered to be important variables in the friction measured at the human skin. In this paper, the contact material, the normal load and the relative velocity are maintained constant in order to decrease the influence of these variables and consequently to limit the number of variables in the statistical analyses.

2.2 Measurements on the skin

The skin hydration and skin temperature were both measured at all assessed anatomical locations. The friction measurements were executed subsequently.

2.2.1 Skin hydration

After completing the questionnaire, the hydration of the skin was measured with a Corneometer (CM825; Courage + Khazaka Electronic GmbH, Cologne, Germany). The hydration of the outermost 10µm is measured with capacitance by pushing the probe onto the skin. The computer software readily returned the hydration in arbitrary units (AU). All anatomical locations were measured three times. When the values for the three measurements showed a variation larger than 10%, the location was tested three times again. The average of the three readings was saved with the data.

2.2.2 Skin temperature

The temperature of the skin was measured before starting the friction measurements. A commercial household thermometer was used to measure the temperature of the skin surface. The thermometer uses infrared to measure the temperature of the skin at a small distance from the skin surface. The temperature was measured two times, and when the temperatures ranged more than 0.3°C, the temperature was re-measured two times again. The average of the two temperatures was registered with the other data for each anatomical location.

2.2.3 Skin friction

Finally, the skin friction was measured with the RevoltST mobile device described by Veijgen et al. (Veijgen et al., 2012a). This portable device is developed specifically for skin friction measurements. For the current study, the device was equipped with an AL6060 aluminium cylinder with a diameter of 20mm, 10mm long and the edge was rounded with a 1mm radius. The aluminium sample had a surface roughness (R_a) of 0.45µm and was cleaned with isopropanol before each measurement condition.

The RevoltST can measure friction forces in the range 0.01 - 6 N. The pre-set normal load was chosen in the middle of the adjustable normal load range (0.5-2 N), so that both low and high coefficients of friction could be measured by the device. In a previous measurement programme, the coefficient of friction was most stable when measuring the interaction between the skin and aluminium. The relative velocity of 10 mm/s was chosen because there was some evidence that the coefficient of friction stabilised faster at higher velocities.

Therefore, the normal force was pre-set on 1.2N and a relative velocity of 10 mm/s. The normal and friction force were logged inside the device with a sample frequency of 2.5kHz. The measurements were executed three times successively.

The friction between the skin and aluminium was tested on three locations on the left upper extremity: the pad of the index finger, the mid-ventral area of the forearm and the mid-dorsal area of the forearm (Figure 1).

The subjects enrolled to the study on site. Therefore, they had followed their usual skin care routine. Their skin was acclimated to the ambient conditions, but not specifically treated for the sake of the measurements. The subjects indicated whether they had washed or treated the skin areas of interest in a certain way in the hour preceding the measurements.

Figure 1 For all anatomical locations on the upper extremity (a) the rotational axis was perpendicular to the length of the arm or finger (b).

2.3 Variables

The variables that are assessed and included in the current study are summarised in Table 1.

Table 1 Variables assessed with their hypothesised contribution.

Figure 2 Images helped to categorise the body type (a) and the amount of hair on the skin (b).

The measured variables

The coefficient of friction is defined as the ratio between the friction force and the applied normal load. In this study, the static coefficient of friction (μ_{static}) is defined as the peak value in the friction signal, as illustrated in Figure 3. In most measurements, this peak value occurred in the first second after movement is initiated. In the few cases in which no peak was visible, the μ_{static} and $\mu_{dynamic}$ are assumed equal. The dynamic coefficient of friction ($\mu_{dynamic}$) is defined as the ratio of the mean value of the data points after the coefficients of friction has stabilised and the normal force.

The hydration in the outermost 10µm of skin is measured with a Corneometer (CM825; Courage + Khazaka Electronic GmbH, Cologne, Germany), and is expressed in arbitrary units (AU). The skin temperature is measured at the surface of the skin, and expressed in °C. The ambient temperature and relative air humidity of the room in which the measurements took place were logged for each measurement location. The temperatures and relative humidity are measured with commercially available equipment and are expressed in °C and % respectively.

Figure 3 The definitions of the static and dynamic coefficient of friction used in this study.

2.4 Subjects

During several days in the spring and summer of 2012, the volunteers were recruited to participate in the study at multiple locations in The Netherlands. In the study, 50 persons (34 men, 16 women; median (interquartile range) age 28 (26) years) volunteered to participate in the study. Before executing the measurements, the participants gave informed consent and provided additional information by completing a single questionnaire. The subject characteristics are summarised in Table 2.

Table 2: characteristics of the subjects

2.5 Statistical analyses

The measured friction data were downloaded into the computer. Matlab (version R2011b; The MathWorks Inc., Massachusetts, USA) was used to obtain the coefficients of friction for each measurement. The data was filtered with a low-pass filter with a cut-off frequency of 20Hz before the coefficients of friction were calculated. The coefficient of friction is defined as the quotient of the friction force and the normal force. The development of the coefficient of friction was roughly the same for all measurements: during the first second after initiating the relative movement between the skin and aluminium, the coefficient of friction showed a peak. After this maximum, the coefficient of friction stabilised to a plateau. The peak indicated the static coefficient of friction whereas the stabilised value was used for the dynamic coefficient of friction (Figure 3).

For the statistical analyses, PASW (version 18.0; SPSS Inc., Chicago, USA) is used. Based on a previous study (Veijgen et al., 2012b), the data are assumed not to be normally distributed. This is checked with a Kolmogorov-Smirnov test (K-S), in which a p-value smaller than 0.05 is used to indicate that the distribution of the data does not follow the bell-shaped normal distribution. Data is represented as median ± interquartile range (range). The median indicates the 50th percentile, meaning that 50% of the values is smaller and 50% of the values has a higher value than the median. The interquartile range indicates the difference between the 75th and 25th percentile. The effect of variables is tested with Mann-Witney U tests (M-W) in case of two variables and Kruskall-Wallis tests (K-W) when more than two variables are compared. The Mann-Witney U test is the nonparametric alternative for the better known t-test and the Kruskall-Wallis test is a nonparametric ANOVA. Correlations between variables are indicated with Spearman's rho (r_s) and the p-value of the correlation is given. Positive correlation coefficients indicate that an increase in the first variable involves an increase in the other variable, whereas a negative correlation coefficient involves an increase in the first variable with a decrease in the other variable.

A significant Spearman's correlation does not necessarily mean that there is a linear relationship between the two variables, as is implied in Pearson's correlation. Curve fitting based on regression analysis is used to determine the nature of the relationship between the significantly related variables. When the explained variance (R^2) is lower than 10%, the equations are omitted. The relationship in such cases is either not strong enough, or can not be described sufficiently by the simple equation.

The static and dynamic coefficient of friction are the primary outcome measures. Skin temperature and skin hydration are secondary outcome measures. For all tests, statistical significance is set at $\alpha = 0.05$. The p-values smaller than 0.05 indicate that there are significant differences or that there is a significant correlation between the variables.

3 RESULTS

Table 3 displays an overview of the results for coefficient of friction, hydration of the skin and skin temperature of all measurements.

Table 3: the median, interquartile range and range for the measured variables.

For each variable assessed in this study, the effect on the dependent variables is calculated. The coefficient of friction is the primary outcome measure, and the skin temperature and the hydration level of the skin are secondary outcome measures. Non-parametric test methods have been used, because the data is not normally distributed (K-S $p \leq 0.04$). Table 4 displays the significant relationships between the variables and the outcome variables.

Table 4 The significant relationships between assessed and outcome variables.

The coefficient of friction as outcome measure

The static and dynamic coefficient of friction

There is a strong correlation between the static and dynamic coefficient of friction: $r_s = 0.95$ ($p < 0.001$). This relationship is linear, with an R^2 of 0.97. The relationship can be described by the following equation:

$$\mu_{dynamic} = 0.85 * \mu_{static}$$

Figure 4 graphically displays the data points with the linear relationship.

Figure 4 The linear relationship between the static and dynamic coefficient of friction.

Hydration

The hydration has a significant effect on the coefficient of friction. The correlation coefficient is 0.51 ($p < 0.001$) for $\mu_{dynamic}$ *as well as* μ_{static}. The relationship is best estimated with a quadratic function ($R^2 = 0.23$):

$$\mu_{dynamic} = -0.12 + 2.6*10^{-2} * Hydration - 1.5*10^{-4} * (Hydration)^2$$

$$\mu_{static} = 2.9*10^{-2} + 2.4*10^{-2} * Hydration - 1.2*10^{-4} * (Hydration)^2$$

This quadratic equation indicates that there is a value for the hydration corresponding to a peak in the coefficient of friction. In the formula of the dynamic coefficient of friction, this peak corresponds to a hydration level of 88 AU. For the static coefficient of friction, this optimum corresponds to a hydration level of 100 AU.

Skin temperature

There is a significant correlation between the coefficients of friction and the temperature of the skin ($r_s = -0.25$; p= 0.004 for $\mu_{dynamic}$ and $r_s = -0.24$; p = 0.005 for μ_{static}). The relationship between the variables can be best approximated with:

$$\mu_{static} = 13.2 - 0.75 * SkinTemp + 1.1*10^{-2} * (SkinTemp)^2$$

$$\mu_{dynamic} = 9.2 - 0.50 * SkinTemp + 7.4*10^{-2} * (SkinTemp)^2$$

The R^2 values for these equations were 0.17 and 0.13 respectively.

Part of the body

The Kruskal-Wallis test for the three locations on the left upper extremity, has shown that the coefficients of friction vary significantly with the anatomical location ($p < 0.001$).The coefficient of friction is highest for the pad of the index finger, whereas the dorsal forearm obtains the lowest coefficient of friction (Figure 5).

Figure 5 The coefficients of friction for the three anatomical locations.

Age and AgeCategory

The age dependent variables Age and AgeCategory are both tested for significant effects. A significant relationship is found between the subject's age and the coefficient of friction ($p = 0.02$ and $p = 0.01$ for μ_{static} and $\mu_{dynamic}$ respectively). For both $\mu_{dynamic}$ and μ_{static} R^2 are smaller than 10%. The positive correlation coefficients of 0.22 and 0.20 indicate that the coefficient of friction increase with increasing age.

When the subjects are categorised in three groups based on their age (younger than 30, 30-50, older than 50) the subjects category older than 50 has significantly higher coefficients of friction (Table 5), when compared to the other categories ($p = 0.02$ for both μ_{static} and $\mu_{dynamic}$). The coefficient of friction for the youngest category is somewhat higher compared to the middle age category, although these differences are not significant.

Figure 6 displays that when the age differences in the coefficients of friction are compared for each body part separately, the differences for the ventral forearm and the index finger are not significant ($p \geq 0.12$). For the dorsal forearm, the coefficients of friction for the older age category are significantly higher than for the other categories ($p = 0.02$ and $p = 0.007$ for $\mu_{dynamic}$ and μ_{static}).

Table 5: The coefficient of friction varies with the variable AgeCategory

Figure 6 The definitions of the static and dynamic coefficient of friction used in this study.

There are some additional age dependent effects found in the dataset. The first effect applies to the older category (the subjects older than 50). The subjects in this category who indicated that they eat fish show significantly higher coefficients of friction compared to those who do not eat fish ($p < 0.001$ for both μ_{static} and $\mu_{dynamic}$).

Furthermore, for the older age category, subjects who indicated that they had not drunk sufficient beverages during the day of the measurements, there are significant differences in the coefficient of friction ($p < 0.05$). The coefficients of friction for the thirsty subjects is lower than for those who had sufficient beverages. This effect is predominantly observed at the pad of the index finger.

Washing in the preceding hour

The subjects indicated whether they had washed the skin area of interest in the hour preceding the measurements, or treated the skin areas with skin care products. The analyses return a significant effect for this variable ($p < 0.001$), although these differences are predominantly caused by the differences in body location. The proportion of the index finger pad is high in the category in which the area of skin has been washed in the hour preceding the test. In one of the previous sections, the index finger pad has already been associated with a higher coefficient of friction than the other assessed anatomical locations. When the analyses are performed again for just the anatomical location index finger, the differences for both dynamic and static coefficient of friction are no longer significant ($p = 0.69$ and $p = 0.33$ respectively).

The presence of hair on the skin

The presence of hair on the skin was assessed by the researcher that performed the measurements. The values ranged from 1 (no or very little hair on the skin sample of interest) to 5 (very hairy skin). The Kruskal-Wallis test for the hair on the skin demonstrates significant differences between categories of the variable hair on the skin ($p < 0.001$ for both $\mu_{dynamic}$ and μ_{static}). The coefficients of friction for the Hair category 1 is higher than for other categories in this variable.

Curve fitting regression analyses present a power relationship as the best fit line. This relationship explained 18% of the variability for the dynamic coefficient of friction, and 16% for the static coefficient of friction.

$$\mu_{dynamic} = 0.98 * (\text{Hair})^{-1.002}$$

$$\mu_{static} = 0.75 * (\text{Hair})^{-0.814}$$

It must be noted that the relationship between the coefficient of friction and the hair present on the surface of the skin is also related to the body location: the index finger pad, which has already been associated with higher coefficients of friction, is hairless. Nevertheless, the body location could not explain all variance in the relationship between the presence of hair and the coefficient of friction.

The subject's height

The height of the subject is significantly correlated with both the dynamic and static coefficient of friction ($r_s = -0.25$ ($p = 0.004$) and $r_s = -0.18$ ($p = 0.039$) respectively). A curve fitting model indicates that only a small part of the variation in the coefficient of friction can be described with a model ($R^2 = 0.05$ for the dynamic coefficient of friction and $R^2 = 0.03$ for the static coefficient of friction), although the correlation coefficients indicate that increasing height is coupled to a decrease in the coefficient of friction.

The height of the subject is significantly correlated with the subject's body mass ($p < 0.001$). Nevertheless, there is no significant relationship between the coefficient of friction and the BMI or BMI category.

The environmental conditions temperature and humidity

The ambient temperature during the measurements also contributes to a change in the coefficient of friction measured at the skin. The correlation is significant ($p < 0.001$) and the correlation coefficient is 0.36 for $\mu_{dynamic}$. The relationship between the ambient temperature and the coefficient of friction is linear as estimated by

$$\mu_{dynamic} = -6.77 + 0.31 * AmbTemp$$

This relationship explains 11% of the variance. The correlation between the static coefficient of friction and the ambient temperature is significant ($r_s = 0.34$), although the R^2 is smaller for the static coefficient of friction ($R^2 = 8\%$).

The relative humidity also has a significant effect on the coefficient of friction. The correlation is $r_s = 0.36$ ($p < 0.001$) for the dynamic coefficient of friction and $r_s = 0.34$ (p <

0.001) for the static coefficient of friction. The relationship can not be sufficiently described with an equation ($R^2 < 0.10$).

Skin hydration as outcome measure

Skin temperature

The measured temperature of the skin is highly correlated with the skin hydration ($r_s = -0.27$; $p < 0.001$). There is a linear relationship between the variables, which explains 21% of the variance between the variables.

$$Hydration = 193.5 - 4.66 * SkinTemp$$

Part of the body

The hydration of the skin is significantly different between the anatomical locations ($p < 0.001$). The hydration levels for the index finger are higher than the ventral forearm while the dorsal forearm results in the lowest coefficients of friction (Table 6).

Table 6: The hydration and temperature of the skin depend on the body location.

Gender

There are no significant effects of gender at a level of confidence of 95%, although with a level of confidence to 90% ($\alpha = 0.10$), the effects of gender are significant ($p = 0.09$). For the two locations on the arm, the hydration level for women is higher than for men whereas for the index finger men have higher hydration levels. The gender differences in hydration are significant for the dorsal forearm ($p < 0.001$) but not for the other locations.

Figure 7 The differences in skin hydration between men and women, for all assessed anatomical locations.

Washing in the preceding hour

Significant differences are found for the variable Washing ($p < 0.001$). For the hydration of the skin, the same applies as for the effect of washing on the coefficient of friction: the effects can largely be ascribed to the large contribution of the anatomical location index finger pad, which has already been associated with higher hydration levels. There are no significant differences in skin hydration between the categories of Washing when comparing the hydration levels for just the index finger.

The presence of hair on the skin

The presence of hair on the skin has a significant influence on the hydration of the skin. Although the differences are partly influenced by the contribution of the high hydration levels for the hairless index finger, the hydration level of the skin decreases with increasing amounts of hair on the skin. This relationship can be described by a power function, with $R^2 = 0.48$, in which the presence of hair is expressed in a numerical value according to Figure 2b:

$$Hydration = 51.3 * (Hair)^{-0.92}$$

Skin temperature as outcome measure

Part of the body

The temperature of the skin varies significantly over the body parts (p = 0.004). The mid-dorsal forearm has the highest temperature, whereas the lowest temperatures are measured on the pad of the index finger (Table 6).

Gender

The skin temperature is lower for women compared to men, when reviewing all data together. When the data is compared for each anatomical location, the differences are significant for the ventral and dorsal side of the forearm, but not for the index finger. This is caused by the large spread in the skin temperature measured on the index finger, which is demonstrated by the large IQR in Table 7.

Table 7: The skin temperature is different for men and women.

The body composition of the subject

There were significant correlations between the skin temperature and both the height and the weight of the subject (r_s = 0.26; p = 0.002 for height; r_s = 0.24; p = 0.004 for weight). Regression analyses provided linear relationships as the best options, although the R^2 values were smaller than 10%. The skin temperature increases with an increase in the weight and height of the subject.

Physical fitness

The subjects indicated their physical fitness on a five point Likert scale, ranging from 1 corresponding to a poor fitness through 5 indicating an excellent fitness.
The skin temperature varies significantly between the categories of Fitness (p = 0.01). The subjects in category 3 have a lower skin temperature than those in category 4. The subjects in category 2 and 5 have the highest skin temperature.

Table 8: The level of fitness influences the skin temperature.

Washing in the preceding hour

The temperature varies significantly for the categories of the variable Washing. It has already been explained in the sections for the other outcome variables that the condition applies mainly to the anatomical location of the index finger. The skin temperature on the index finger is significantly lower when the subject had washed the hands or treated them with skin care products within an hour before the measurements (p = 0.01).

Time of the day

The effect of the time of the day on the temperature of the skin is significant (p = 0.020). The differences are predominantly caused by the temperature on the index finger pad (p = 0.007). Table 9 shows that the temperature was lowest for the late morning and highest for the early afternoon.

Table 9: The skin temperature varies with the time of the day.

Air humidity

A significant correlation is observed between the temperature of the skin and the air humidity ($r_s = 0.20$; p = 0.017). The skin temperature increases when the relative air humidity increases, although the explained variance can not be sufficiently described with a curve fitted model (linear equation, $R^2 = 0.08$).

DISCUSSION

In the construction of the questionnaire, the choice of variables is based on the literature. The variables that are admitted in the questionnaire have been associated with changes in the frictional properties or changes in the skin's properties. The objective of the current study is to relate these variables to the coefficients of friction, skin hydration and skin temperature. The results are based on almost 500 skin friction measurements at in vivo human skin.

The range in the results is large: the total range in the coefficients of friction is 0.05 - 3.6 and 0.07 - 3.9 for $\mu_{dynamic}$ and μ_{static} respectively, the hydration varies between 4 AU and 112 AU, and the skin temperature between 22.5 °C and 35.6 °C.

In the literature, the variation is often attributed to the use of different measuring equipment and variations in methods, and regarded as problems in the accuracy. Researchers try to avoid this variability by cleaning the skin with chemicals, such as ether and alcohol. The effect of skin hydration is are often simulated, by artificially increasing the hydration by means of applying water onto the surface of the skin.

In the current study, only one measuring device is used, all measurements are executed by the same researcher and the same procedure is followed for the measurements at different subjects. In this study, the variability in the measurement results is not regarded as problem, but rather treated as inevitable result of interpersonal variety. Statistical analyses are used to determine the probability whether the differences between the variables is caused by the influential variable or by chance alone. For such an analysis, a large set of data is essential, because with small datasets, the actual effect of variables on the coefficient of friction cannot be determined with sufficient confidence.

The analyses serve the purpose of identifying the relationships between the potential influential variables and the outcome measures: the coefficients of friction, the hydration of the skin and the skin temperature.

Data collection

The correct and repeatable assessment and quantification of the input variables is important for the outcomes of the statistical analysis. However, the accuracy of the data collection is limited by the amount of time that the subjects are willing to spend and the level of intrusion into their privacy that they will allow. Consequently, in some cases, arguably a subjective method has been used for the assessment of the variables. Two examples are the estimation of the amount of hair and the fitness level of the subjects. The amount of hair was estimated based on the illustration in Figure 2. The variability of the assessment was limited by having just one researcher do all assessments, and by performing them all on a single day. For investigations involving multiple researchers over a longer time period, a better assessment method has to be developed. The physical fitness of the subjects was quantified using a self-assessment by the subjects, which is likely to create a bias. It was noticed that the extreme values in the self-assessment ('*poor*' and '*excellent*') were not often used. If needed, it would be possible to obtain a more substantiated estimate of the subject's fitness, e.g. by expanding the questionnaire with several fitness related questions or asking the subjects to participate in a physical condition test, e.g. on a tread mill.

The mutual relationships between the outcome variables

The current study finds a linear relationship between the dynamic and static coefficient of friction. For almost all measurements $\mu_{dynamic}$ is smaller than $\mu_{static.}$ The multiplication factor 0.85 was also obtained by the authors in a previous study (Veijgen et al., 2012b), with friction measurements between skin and a range of materials under a variety of loads and velocities. They reported that $\mu_{dynamic}$ was a factor 0.85 smaller than μ_{static}, which compares to the factor in the current study. This factor was obtained between the skin at the upper extremity and various materials, with loads ranging from 0.5-2N and relative velocities ranging from 1-10 mm/s.

The hydration of the skin affected both $\mu_{dynamic}$ and μ_{static}. The percentage of the variability that is explained by the quadratic relationship (23%) is lower than expected. The Corneometer value gives an indication for the hydration of the stratum corneum. The stratum corneum is the outermost layer of the skin, which is in contact with the contact material in skin friction measurements. In the literature, this layer is regarded as the most important layer in skin friction (Koudine et al., 2000; Van Kuilenburg et al., 2012; Yuan and Verma, 2006). Therefore, the effect of hydration on skin friction was expected to be more pronounced.

In the current study, an increase in hydration corresponds to an increase in coefficient of friction, until a maximum in skin friction is reached and from that point there is a decrease in the coefficient of friction with increasing hydration levels. The majority of the studies found that the coefficient of friction increased with increasing hydration (El-Shimi, 1977; Gerhardt et al., 2008b; Hendriks and Franklin, 2012; James et al., 1994; Sivamani et al., 2003; Tomlinson et al., 2011). However, it must be noted that in most studies the hydration of the skin was artificially increased by applying water to the skin or to soak the skin in water for a certain period of time. Tomlinson et al. (2011) have also reported an optimum in the relationship between the coefficient of friction and the natural hydration of the skin. The peak in the coefficient of friction was obtained at a comparable hydration level as found in the current study (approximately 100AU, as measured with a Corneometer).

The relationship between the coefficients of friction and the skin temperature can be described by a quadratic equation as well. The coefficient of friction decreased with increasing skin temperature. Elleuch et al. (2007) reported that the adhesion between the skin and contact material is influenced by the temperature of the skin, although the nature of the contribution is unknown.

Skin temperature as outcome variable

There were some variables that only significantly affected the temperature of the skin and not the coefficient of friction or the hydration of the skin. Those variables were gender, body mass, fitness and time of the day. The effects of most of these variables on the temperature are expected based on the physiological properties: the temperature of the skin depends on the body's core temperature (Kräuchi, 2002). The temperatures are susceptible to circadian rhythms: the temperature of the body and of the skin changes over the day. The temperature of the body is an equilibrium between the heat generated by the body and the amount of heat dissipated, for example through the skin. Variables such as fitness and body weight have effect on the physiological processes in an individual, which can result in a shift in the heat balance (James et al., 1994; Kräuchi, 2002; Widmaier et al., 2006; Wilmore and Costill, 2004;).

Influential variables for skin friction, hydration of the skin and skin temperature

Large variations were found between the coefficients of friction for the three anatomical locations. The coefficient of friction obtained on the pad of the index finger was generally higher than the friction on the locations on the forearm. In the literature, the anatomical location is held to be an important variable for skin friction (Bertaux et al., 2010; Childs and Henson, 2007; 29,Cua et al., 1990; Fagiani et al., 2011; Gitis and Sivamani, 2004; Hendriks and Franklin, 2012; Koudine et al., 2000; 108,130,Zhang and Mak, 1999; Zhu et al., 2011). Even on a location as the ventral forearm, there are differences in skin properties and friction between the proximal and distal aspect (Gitis and Sivamani, 2004).The significant results for the variables *Washing* and *Hair* could be largely ascribed to the distribution of the body parts over the categories of the *Washing* or *Hair* variables. For example, there was no significant effect of washing the skin in the preceding hour when the coefficients of friction for just the index finger were compared.

The variable height was significant, although the variability explained with the relationships was very low. The observed correlation between height and friction is not easily explained, but it is tempting to speculate as to the causes: when comparing a tall and a short person with the same BMI, they will have a different body composition and, consequently, different thicknesses of their skin. This might manifest itself in the observed correlation between height and skin friction. In the literature, the body composition, or height has not often been associated with the frictional properties of the skin (Bullinger et al., 1979). It is unclear whether these effects have not been examined or were not present in other studies.

Between the age of the subject and the coefficients of friction, significant correlations were found, although the found relationships were not strong enough to explain more than 10% of the variance between the variables. The division in age categories shows that the coefficient of friction is lowest for the 30-50 year old category. In skin friction literature, there is no consensus on the effect of age on the coefficient of friction: some studies find a relationship (Asserin et al., 2000; Childs and Henson, 2007; Fagiani et al., 2011; Lewis et al., 2000; Pailler-Mattei and Zahouani, 2006; Zhu et al., 2011), while others find no significant differences (Besser et al., 2008; Cua et al., 1990; Gerhardt et al., 2009; Gitis and Sivamani, 2004). The mechanisms by which the age of the subject would influence the coefficient of friction remains unclear from the literature. It is widely believed that age affects the skin in many ways, for example the skin layer thickness, the cell development, anisotropic behaviour and strength (Arumugam et al., 1994; Asserin et al., 2000; Edwards and Marks, 1995; Flynn et al., 2011; Gerhardt et al., 2009; Gross et al., 1992; James et al., 1994; Koudine et al., 2000; Kvistedal and Nielsen, 2007; Langer, 1978a; Pailler-Mattei and Zahouani, 2006; Rawlings, 2006; Widmaier et al., 2006; Wilmore and Costill, 2004;,Zahouani et al., 2011; Zhu et al., 2011). All these variables consecutively can influence the tribology of skin. The low value of R^2 of the curve fitted model indicates that that the effects cannot be described sufficiently using the age of the subject as the main variable.

The environmental conditions in which the measurements were executed significantly influenced the coefficient of friction. The ambient temperature and relative air humidity were not controlled in the rooms in which the measurements were executed. Therefore, the ambient temperature and relative air humidity varied and data were registered for each measurement. There was a linear relationship between the coefficient of friction and the ambient temperature. In the literature, the ambient temperature is mentioned to influence the frictional behaviour of skin (Bertaux et al., 2010; Bobjer et al., 1993; Childs and Henson, 2007; Elleuch et al., 2007) as well as the skin's properties (Edwards and Marks, 1995; James et al., 1994; Kräuchi, 2002; Kvistedal and Nielsen, 2007; Pailler-Mattei and Zahouani, 2006; Papir et al., 1975; Widmaier et al., 2006; Wilmore and Costill, 2004;).

The air humidity has also been associated with skin friction (Bertaux et al., 2010; Bobjer et al., 1993; Derler et al., 2012; Gerhardt et al., 2008) and with the skin's properties (Hendriks and Franklin, 2012; Rawlings and Harding, 2004; Sivamani et al., 2003; Widmaier et al., 2006). High levels of relative air humidity have been associated with accumulation of water in the stratum corneum. However this effect has only been observed at values for the air humidity over 70% (Bouwstra et al., 2008; Gitis and Sivamani, 2004; Papir et al., 1975; Rawlings and Harding, 2004). The maximum value for the air humidity in the present study was 59%. The obvious conclusion is that the environmental conditions constitute the environment in which the measurement takes place. However, as the skin is a living material, the influence of the environmental conditions can lead beyond this environment. As an example, extremely theoretical statement: it is possible that an increase in the ambient temperature leads to an increased sweat production (Edwards and Marks, 1995; James et al., 1994). The acid sweat increases the pH of the skin (Bettley, 1960), which in turn affects the coefficient of friction (Adams et al., 2007). The exact mechanisms of how skin characteristics change the frictional behaviour of the skin remain unknown and are outside the scope of this paper. Nevertheless, the significant contribution of environmental temperature and air humidity can be a reason for more extensive research. Moreover, the next progressive step towards the prevention of friction related skin injuries can be the determination of the mechanisms by which the important variables influence the frictional behaviour of the living human skin.

CONCLUSIONS

In this study, skin friction, skin temperature and the hydration of the skin are related to variables on the human skin, subject characteristics and environmental conditions.

Significant differences in the coefficient of friction were found for the anatomical location. Furthermore, the coefficient of friction tends to increase with increasing age, increasing ambient temperature and increasing relative air humidity, whereas the friction decreases with increasing amounts of hair on the skin and with the subject's height. There were also differences in the skin hydration when measured on different body locations. Both the coefficient of friction as the skin hydration were higher at the pad of the index finger. The skin hydration decreased with increasing skin temperatures and increasing amount of hair on the skin. The hydration was dependent of gender. For the temperature of the skin, significant differences were found for gender, body mass, fitness and time of the day.

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Table 1 Variables assessed with their hypothesised contribution.

Variables in the questionnaire	
Age	The age of the subject is expressed in years. In the literature, there is no consensus on the contribution of age on the frictional properties (Asserin et al., 2000; Besser et al., 2008; Childs and Henson, 2007; Cua et al., 1990; Fagiani et al., 2011; Gerhardt et al., 2009; Lewis et al., 2000; Pailler-Mattei and Zahouani, 2006; Zhu et al., 2011), but the influence on the skin's properties has been widely accepted (Arumugam et al., 1994; Asserin et al., 2000; Edwards and Marks, 1995; Flynn et al., 2011; Gross et al., 1992; James et al., 1994; Kvistedal and Nielsen, 2007; Pailler-Mattei and Zahouani, 2006; Widmaier et al., 2006; Wilmore and Costill, 2004; Zahouani et al., 2011; Zhu et al., 2011), for example that the skin relief increases with increasing age (Asserin et al., 2000; Flynn et al., 2011; Gerhardt et al., 2009; Koudine et al., 2000; Zahouani et al., 2011).
Gender	Most tribological studies on skin demonstrated that there are no significant gender differences for the coefficient of friction (Besser et al., 2008; Cua et al., 1990; Gerhardt et al., 2008b; Gerhardt et al., 2009; Gitis and Sivamani, 2004; Sivamani et al., 2003). There are some gender differences for skin properties (Flynn et al., 2011; Gerhardt et al., 2008b; James et al., 1994; Kvistedal and Nielsen, 2007; Zhu et al., 2011) such as elasticity (Dick, 1947).
Height	The subject's height (in cm) has been associated with the coefficient of friction (Bullinger et al., 1979) in the form of body composition. The subject's height is also used for the calculation of the body mass index of the subject.
Body mass	The weight of the subject is expressed in kg. Body weight has been related to skin thickness (Alexander and Miller,1979; De Morree, 2000; Widmaier et al., 2006; Wilmore and Costill, 2004), and skin tension (Langer, 1978a). The subject's body weight is used for the calculation of the body mass index of the subject.
Skin treatment	Subjects indicated whether they washed their hand or used skin care products in the preceding hour. These skin treatments temporarily change the friction measured on the human skin (Asserin et al., 2000; Besser et al., 2008; Fagiani et al., 2011; Gerhardt et al., 2008b; Gitis and Sivamani, 2004; Hendriks and Franklin, 2012; James et al., 1994; Koudine et al., 2000; Lewis et al., 2000; Sivamani et al., 2003; Tomlinson et al., 2011; Zhu et al., 2011).
Physical fitness	The subjects indicated their physical fitness on a 5-point Likert scale. Physical fitness influences the skin properties by modulations in evaporation (Madison, 2003; Widmaier et al., 2006; Wilmore and Costill, 2004) and blood supply (De Morree, 2000).
Eating and drinking	Subjects indicated whether they ate some meat or fish, or drank any alcoholic beverages in the week before the measurements. In the literature, these are indicated as influential variables for the skin properties (James et al., 1994; De Morree, 2000; Rawlings, 2006; Widmaier et al., 2006; Wilmore and Costill, 2004). For example, the skin would benefit from eating fish but not from eating meat (Rawlings, 2004).
Fluid intake	The subjects indicated whether they drank sufficient beverages on the day of the measurements. The skin properties change when people are thirsty (Gross et al., 1992; James et al., 1994; De Morree, 2000).
Variables assessed by the researcher	
Skin colour	The skin colour was scored by the researcher. The skin colour range from 1 to 3, in which 1 is light skin and 3 is dark skin. The skin colour is an indicator for the composition and cell development of the skin (Anderson and Parrish, 1981; De Morree, 2000; Rawlings, 2006).

Body type	The body type was assessed for each subject. Number 1 corresponded to the ectomorph somatotype, 3 to the mesomorph and 5 to the endomorph (Figure 2). In the literature, body type has associated with the coefficient of friction (Bullinger et al., 1979). In endomorph people, the contribution of the fatty subcutis is relatively large, whereas in mesomorph or ectomorph people underlying tissues such as muscles and bones, respectively, are more important.
Presence of hair	The amount of hair that was present on the skin area of interest was indicated for each anatomical location. The amount of hair was scored on a five point scale, in which 1 indicated no to very little hair on the skin and 5 corresponded to very hairy skin. In the literature, no studies have been found to report on the effects of the presence of hair on the skin's properties, but in general, hair is assumed to influence skin friction albeit as an unwelcome disturbance.
Time of the day	The day was divided into five periods. The skin properties depend on the time of the day (Madison, 2003; De Morree, 2000; Rawlings, 2006; Widmaier et al., 2006; Wilmore and Costill, 2004). The researcher indicated when the measurements took place: in the early morning (7-10hr), late morning (10-12.30hr), early (12.30-15hr) or late afternoon (15-18hr), or evening (18-22hr).
Calculated variables	
Body mass index	The body mass index (BMI) can be used as an indication for the subject's body composition. In the literature, this is associated with the skin's properties (Bullinger et al., 1979; James et al., 1994; De Morree, 2000,Widmaier et al., 2006; Wilmore and Costill, 2004).
BMIcategory	Based on their BMI, subjects were categorised in four categories: underweight (<18.5), normal (18.5-25), overweight (25-30) and obese (>30).
AgeCategory	The subjects were divided into categories based on their age. The age categories were younger than 30, 30-50 and older than 50. According to some studies, the body develops until the age of 30, then skin properties change slowly and after the age of 50 the skin changes faster (Arumugam et al., 1994; Edwards and Marks, 1995; Gerhardt et al., 2009; Rawlings, 2006; Zahouani et al., 2011).

Table 2: characteristics of the subjects

Number	**50**	
male	34	
female	16	
Age		
median	28	years
interquartile range	26	years
range	1-82	years
Height		
median	180	cm
interquartile range	17	cm
range	89-199	cm
Weight		
median	76	kg
interquartile range	22	kg
range	13-128	kg
BMI		
median	23.8	kg/m^2
interquartile range	4.3	kg/m^2
range	16.4-36.6	kg/m^2
BMI category		
underweight	3	
normal	31	
overweight	15	
obese	1	
Skin colour		
light	41	
medium	8	
dark	1	
Physical fitness		
poor	3	
average	13	
good	28	
excellent	6	

Table 3: the median, interquartile range and range for the measured variables.

	μ_{static}	$\mu_{dynamic}$	***Hydration*** AU	***SkinTemp*** °C
median	0.73	0.62	38.7	32.5
IQR	0.92	0.76	31.9	2.3
minimum	0.10	0.08	4	22.5
maximum	3.86	3.64	112	35.6

Table 4 The significant relationships between assessed and outcome variables.

		$\mu_{dynamic}$	μ_{static}	**Hydration**	**SkinTemp**
Variable	Test	p-value	p-value	p-value	p-value
Measured variables					
μ_{static}	r_s	0.000**	-		
Hydration	r_s	0.000**	0.000**	-	
SkinTemp	r_s	0.000**	0.005**	0.001**	-
Measurement variables					
Part of the body	K-W	0.000**	0.000**	0.000**	0.004**
TimeOfDay	K-W	-	-	-	0.020*
AmbTemp	r_s	0.000**	0.000**	-	-
AirHumidity	r_s	0.005**	0.036*	-	0.017*
Subject variables					
Age	r_s	0.011*	0.022*	-	-
AgeCategory	K-W	0.002**	0.015*	-	-
Gender	M-W U	-	-	-	0.006**
Height	r_s	0.004**	0.039*	-	0.006**
BodyMass	r_s	-	-	-	0.012*
BMI	r_s	-	-	-	-
BMIcategory	K-W	-	-	-	-
BodyType	K-W	-	-	-	-
SkinColour	K-W	-	-	-	-
Fitness	K-W	-	-	-	0.010**
EatingMeat	M-W U	-	-	-	-
EatingFish	M-W U	-	-	-	-
DrinkAlcohol	M-W U	-	-	-	-
FluidIntake	M-W U	-	-	-	-
Skin variables					
Washing	K-W	0.000**	0.000**	0.000**	0.005**
Hair	K-W	0.000**	0.000**	0.000**	-

* Significant at the 0.05 level.
** Significant at the 0.01 level.

Table 5: The coefficient of friction varies with the variable AgeCategory

	all		**< 30**		**30-50**		**> 50**	
	median	(IQR)	median	(IQR)	median	(IQR)	median	(IQR)
$\mu_{dynamic}$	0.62	(0.76)	0.51	(0.69)	0.31	(0.76)	0.92	(0.74)
μ_{static}	0.73	(0.92)	0.67	(0.89)	0.48	(0.95)	0.98	(0.69)

Table 6: The hydration and temperature of the skin depend on the body location.

	all		**FA(V)**		**FA(D)**		**IF(P)**	
	median	(IQR)	median	(IQR)	median	(IQR)	median	(IQR)
Hydration	38.7	(31.9)	38.8	(15.6)	25.5	(15.4)	80.3	(36.6)
Temperature	32.5	(2.3)	32.8	(1.2)	33.0	(1.7)	30.3	(7.3)

Table 7: The skin temperature is different for men and women.

	all		**FA(V)**		**FA(D)**		**IF(P)**	
	median	(IQR)	median	(IQR)	median	(IQR)	median	(IQR)
men	33.0	(2.4)	33.1	(1.2)	33.1	(1.4)	30.9	(7.1)
women	32.1	(1.9)	32.5	(0.6)	32.0	(1.1)	29.3	(7.2)

Table 8: The level of fitness influences the skin temperature.

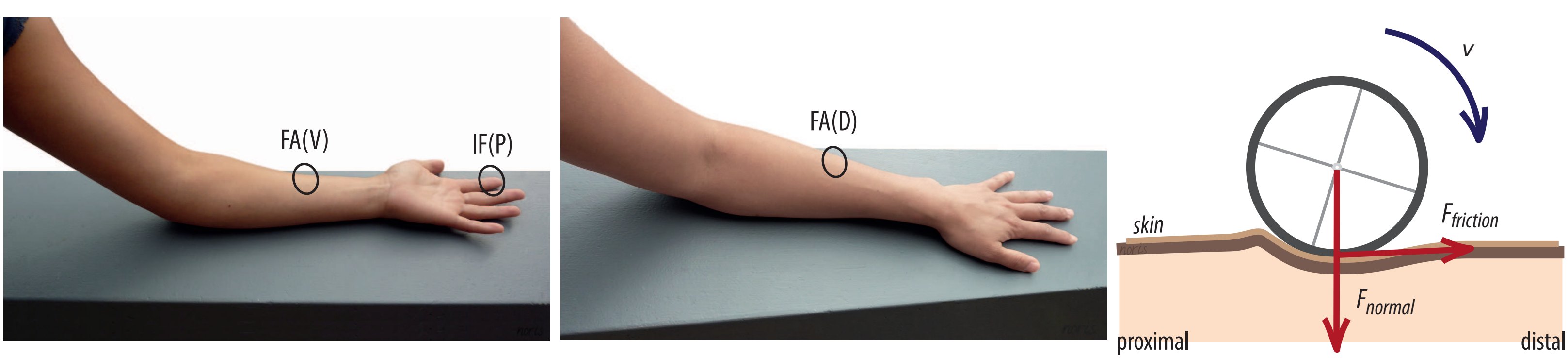
	2		3		4		5	
	median	(IQR)	median	(IQR)	median	(IQR)	median	(IQR)
SkinTemp	33.3	(2.3)	31.4	(1.9)	32.8	(2.1)	33.1	(2.4)

[a] None of the subjects indicated the physical fitness as being poor.

Table 9: The skin temperature varies with the time of the day.

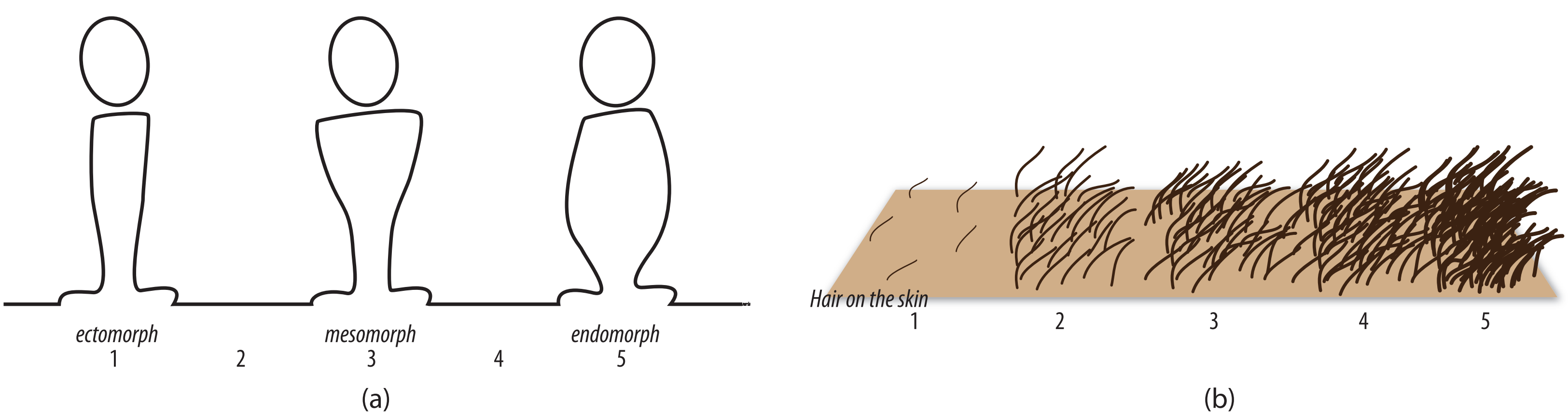
	all		**FA(V)**		**FA(D)**		**IF(P)**	
	median	(IQR)	median	(IQR)	median	(IQR)	median	(IQR)
late morning	32.2	(3.3)	32.5	(1.0)	32.3	(1.4)	27.1	(5.3)
early afternoon	33.1	(2.5)	33.1	(1.9)	33.1	(1.4)	30.3	(5.9)
late afternoon	32.6	(2.2)	32.8	(1.2)	32.6	(1.9)	32.2	(6.5)

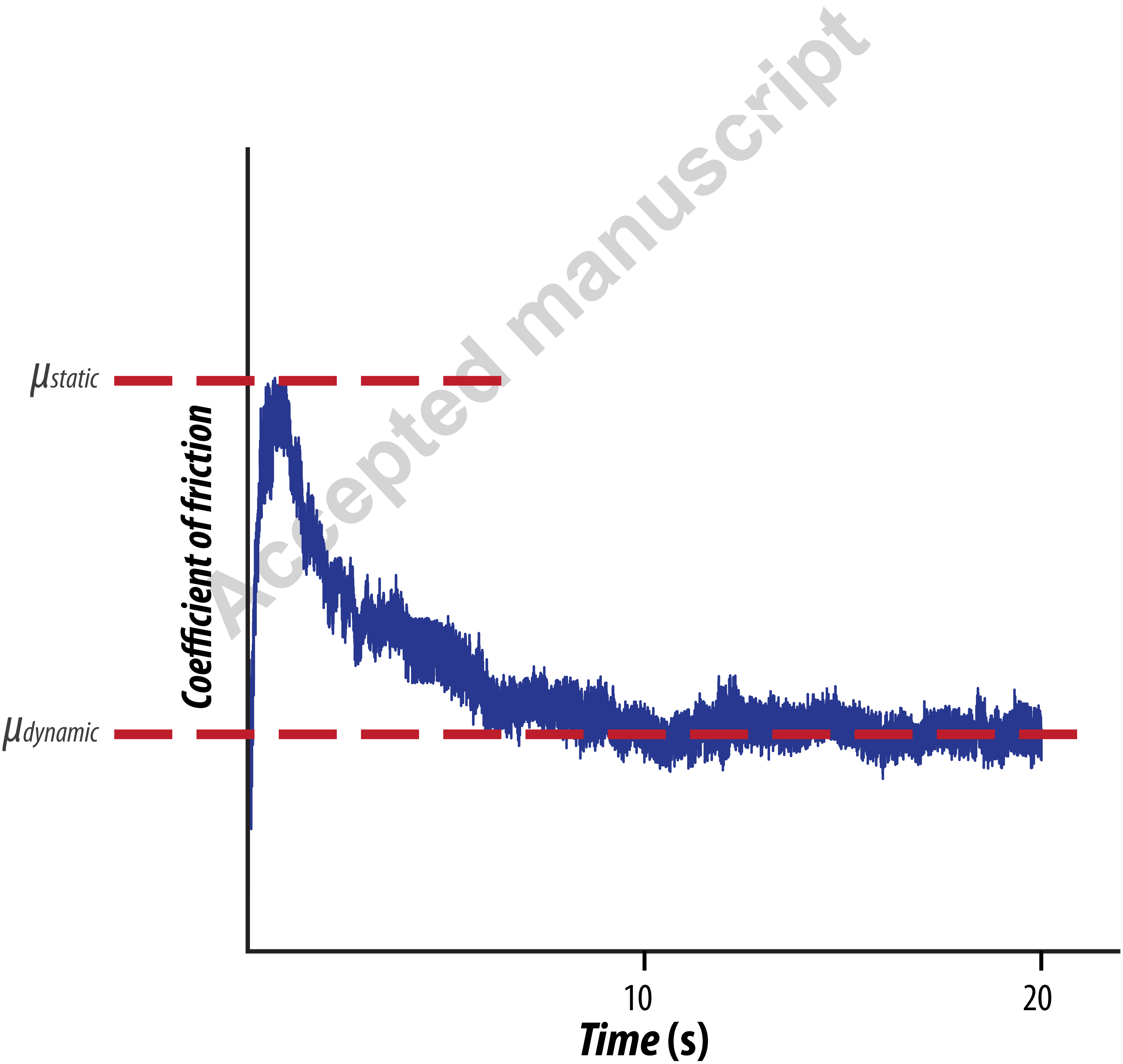
Figure



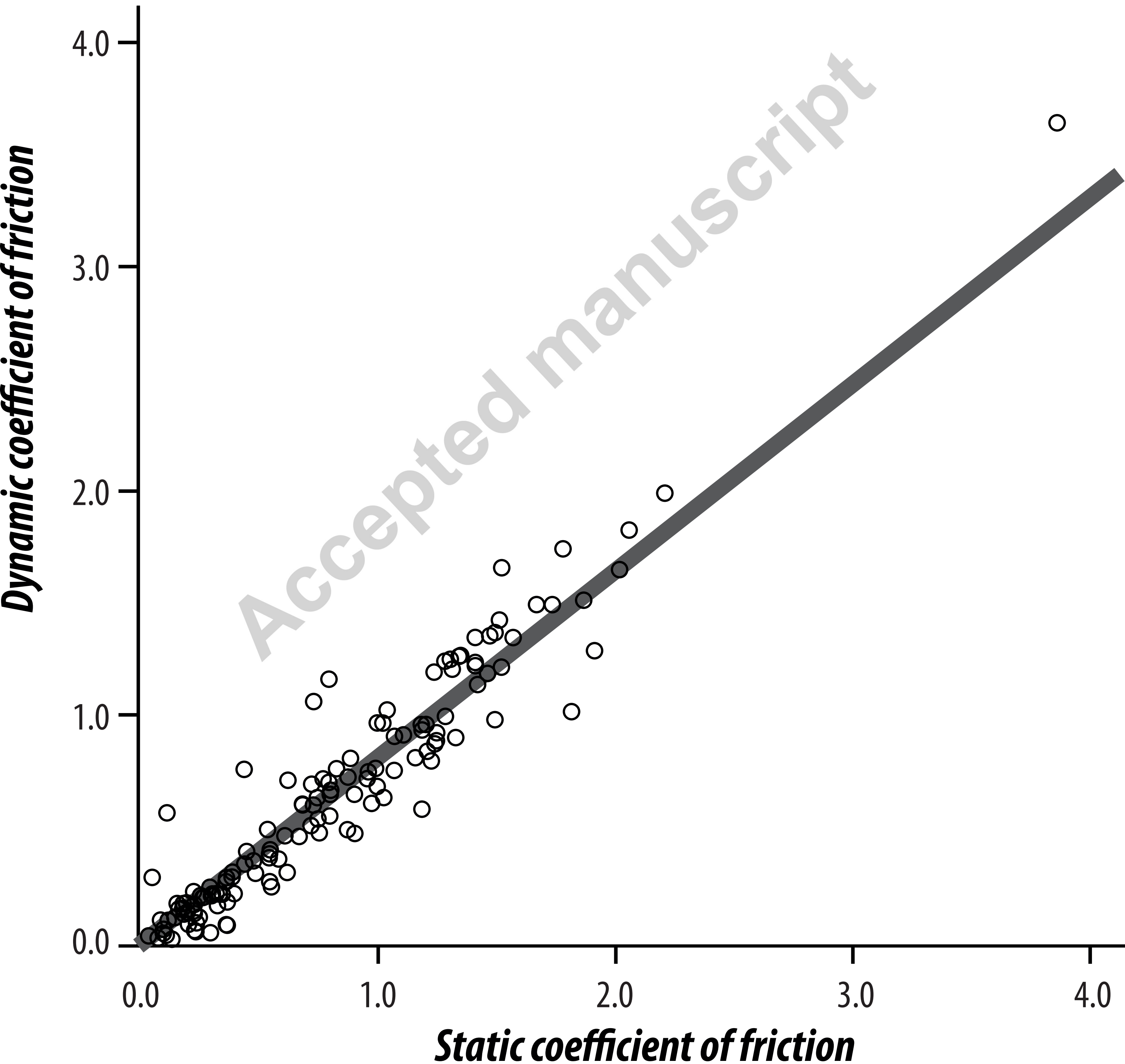
(a) (b)

Figure


ectomorph
1
2
mesomorph
3
4
endomorph
5
(a)
Hair on the skin
1
2
3
4
5
(b)

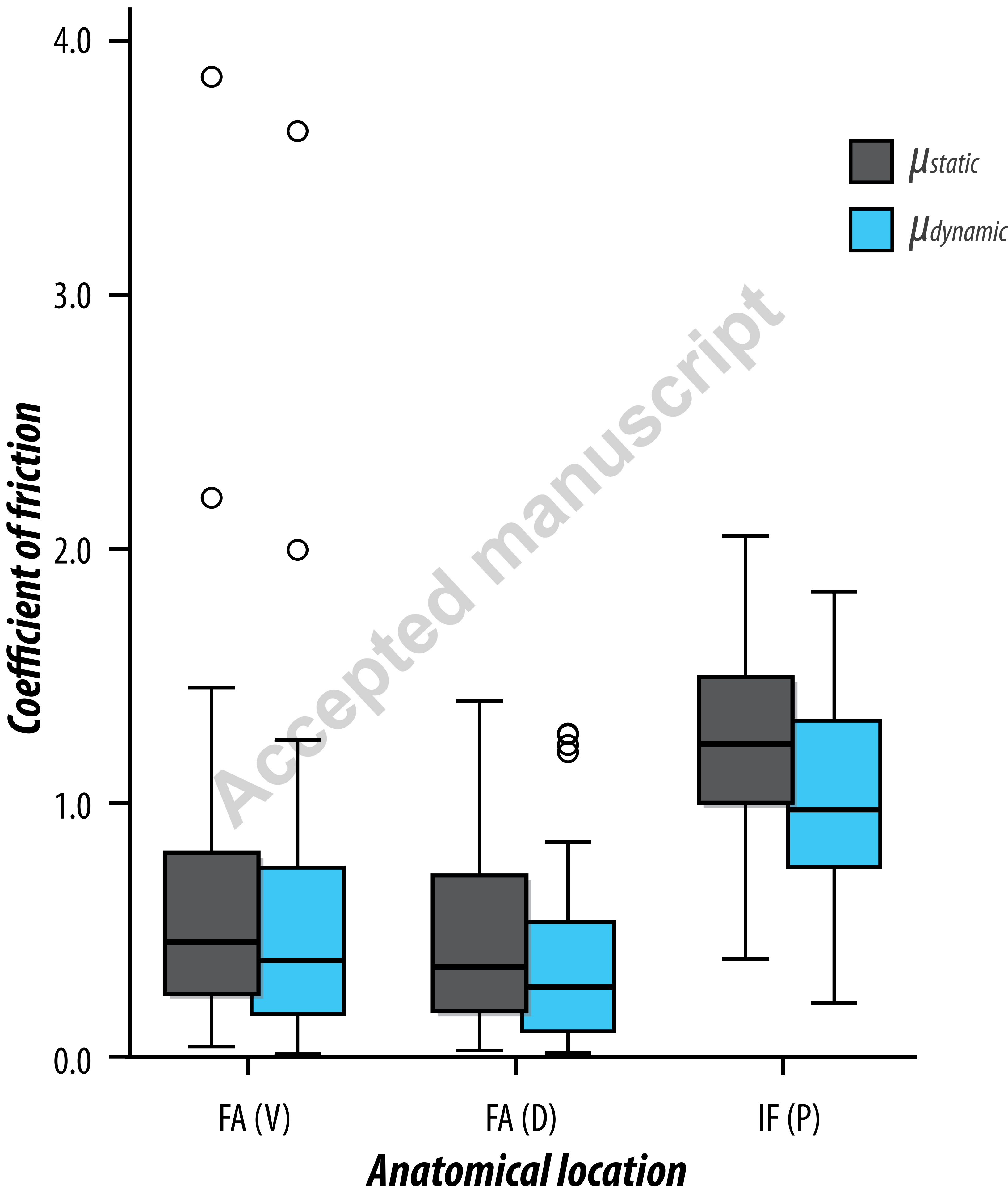

μstatic
μdynamic
Coefficient of friction
10
20
Time (s)
Accepted manuscript

Figure



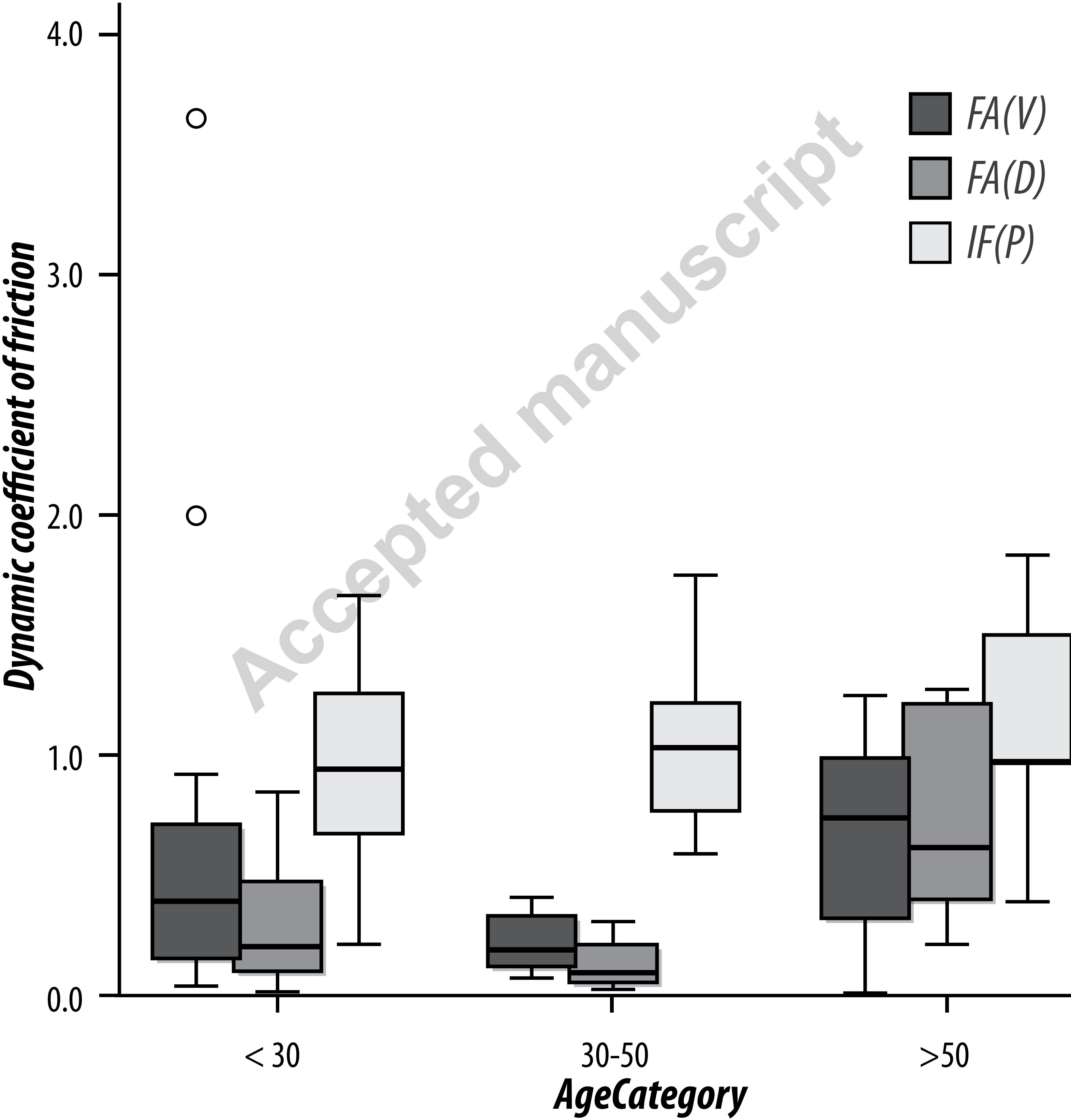
4.0
3.0
2.0
1.0
0.0
Dynamic coefficient of friction
0.0
1.0
2.0
3.0
4.0
Static coefficient of friction
Accepted manuscript

Figure

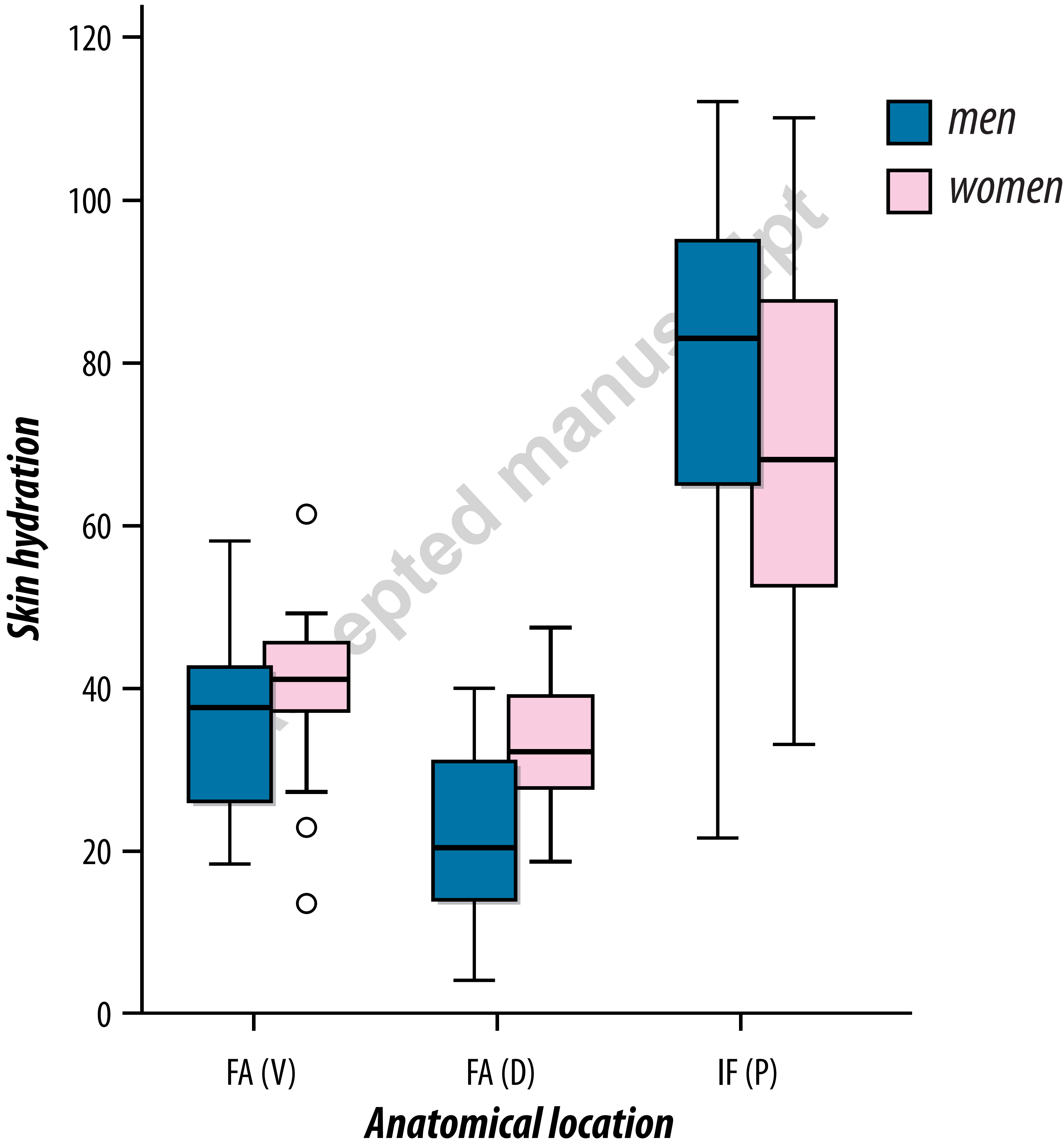


4.0
3.0
2.0
1.0
0.0
Coefficient of friction
μstatic
μdynamic
FA (V)
FA (D)
IF (P)
Anatomical location

Figure


4.0
3.0
2.0
1.0
0.0
Dynamic coefficient of friction
FA(V)
FA(D)
IF(P)
< 30
30-50
>50
AgeCategory

Figure



120
100
80
60
40
20
0
Skin hydration
men
women
FA (V)
FA (D)
IF (P)
Anatomical location