ACTA ORTHOPAEDICA et TRAUMATOLOGICA TURCICA

www.aott.org.tr

Research Article

Evaluation of braking performances of patients with osteoarthritis of the knee or hip: Are there alternatives to a brake simulator?

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ARTICLE INFO

Article history:
Submitted July 10, 2019
Received in revised form February 14, 2020
Last revision received November 16, 2020
Accepted December 8, 2020

Keywords:
Automobile driving
Osteoarthritis
Hip replacement
Knee replacement
Arthroplasty
Rehabilitation

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ABSTRACT

Objective: This study aims to develop and evaluate a simple tool for daily practice that might allow a rough estimate of individual braking performance (brake response time, BRT) of patients with osteoarthritis or those with arthroplasty of the knee or hip.

Methods: In this cross-sectional study, we examined 162 patients (72 men, 90 women; mean age = 64±12.8 years) who suffered from osteoarthritis of the knee (n=45) or hip (n=64) or who underwent a total hip (n=37) or knee (n=16) arthroplasty. BRT of each patient was measured in a brake simulator. The results were compared to demographic data, various clinical tests, and pain surveys. From these data, a multiple linear regression model was developed.

Results: From the observed correlations, the regression model consisted of age (correlation with BRT τ=0.176, p=0.001), sex (τ=0.361, p<0.001), Hau's step test (τ=-0.345, p<0.001), and the pain dimension of the Hip disability/Knee injury and Osteoarthritis Outcome Score (τ=-0.265, p<0.001). We, therefore, suggested the following formula: BRTest = 634.8 - (8.8 x Hau) + 119.2 (for women) + (3.0 x age) - (1.3 x H/KOOS Pain). The above-mentioned variables contributed significantly to the prediction of BRT and could achieve a multiple R^2 adj of 0.31. The model leaves a residual standard error (i.e., SD of the residuals) of 158.4 ms, which is superior to a model without predictors; F (4.140)=16.8, p<0.001.

Conclusion: Our evaluated regression model offers an uncertainty which is comparable to the one based on a fixed time period after surgery or a defined pathologic condition. The high variability even within a single patient over several brake simulator measurements makes it unlikely for a model to be generated solely based on clinical testing. Taking the available data in literature into account, we advise caution when formulating a real-time- or condition-based recommendation. We rather suggest being aware of risk factors that might lead to impaired BRT to sensitize patients to their impaired ability to drive. We identify such risk factors, namely old age, female sex, impaired musculoskeletal function, as tested in Hau's step test, and high levels of pain.

Level of Evidence: Level III, Therapeutic Study

Introduction

Modern society imposes high demands on individual flexibility, which applies decidedly to driving a car. Annual total kilometers driven in the United States increased threefold from 1960 to 2000 (1, 2). Moreover, with the age of the population in modern societies rising, the number of elderly drivers is also increasing (1). Planek (1981) suggested that drivers older than 55 are at higher risk of being liable for an accident than younger drivers. Interestingly, those accidents are often related to problems of perception and decision-making (3, 4). This leads to the crucial question: Until what age—or rather under what physical conditions—can driving a car be considered safe? The legal framework concerning driving capability varies by country. It is mandatory for drivers to report disabling conditions to the Driver and Vehicle Licensing Agency in the United Kingdom for review, whereas in Germany, it is the responsibility of the driver to ensure safe driving ability in traffic (5). Automobile driving is a complex task requiring a variety of skills that must be mastered. One key element that is frequently used in ergonomic studies is the ability to adequately perform emergency braking. Various thresholds have been suggested by different road authorities for the maximum time allowed to trigger full braking, with most being approximately 700 ms (6, 7).

Patients with osteoarthritis (OA) of the lower extremities or those having undergone knee or hip arthroplasty often ask their treating physicians if their condition allows continued automobile driving. With more than 2.5 million individuals with hip replacements and 4.7 million with knee replacements in the United States alone, as well as an estimated incidence of radiographically proven OA in approximately 80% of adults over 75 years in the Western population, the question of when a patient is fit for driving with these conditions is of high importance and has been the focus of scientific investigation in recent years (8, 9). From these studies, general recommendations have been formulated: For both right-side total hip and total knee arthroplasty, it has been suggested that individuals refrain from driving for 4 to 8 weeks (10-13). Patients with OA, however, also show impaired braking

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Cite this article as: *von Bernstorff M, Bausenhart F, Rapp J, Feierabend M, Ipach I, Hofmann UK. Evaluation of braking performances of patients with osteoarthritis of the knee or hip: Are there alternatives to a brake simulator? Acta Orthop Traumatol Turc 2021; 55(1): 42-7.*

DOI: 10.5152/j.aott.2021.19041

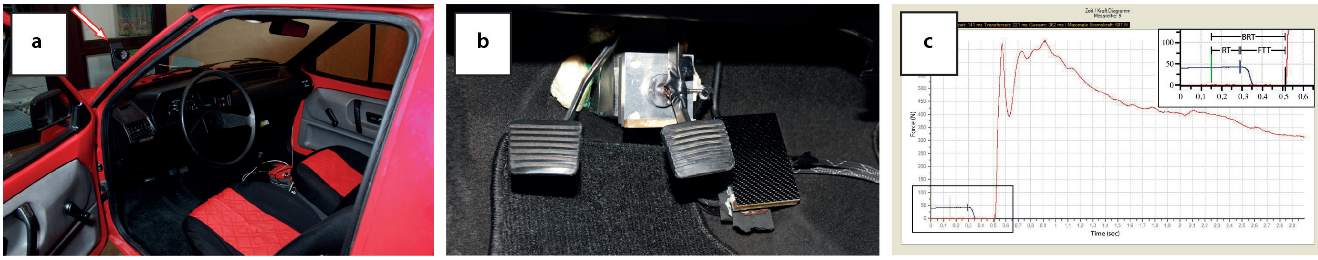

Figure 1. a-c. (adapted from [14]). Brake simulator and recorded data: (a) Custom-made brake simulator in a Volkswagen Polo to measure brake force and brake response time (BRT), with its components reaction time (RT) and foot transfer time (FTT), the arrow indicating the red LED. (b) Accelerator and brake pedal on the right and in the middle, respectively, both equipped with a pressure sensor. The clutch pedal is on the left. (c) Computer output data showing RT, FTT, BRT, and maximum brake force. The top right insert is an enlargement of the lower left section of the graph. The horizontal black line at the beginning of the graph displays the pressure on the accelerator. Vertical green line: triggering of the red emergency signal. Vertical blue line: beginning of pressure decrease on the accelerator pedal. No pressure is registered while the foot is being transferred to the brake pedal. Vertical black line on the right: beginning of pressure increase on the brake pedal, as shown in the red graph

performance when compared to an age-matched control sample (14). The problem with these findings and recommendations is that the wide variability within these groups makes it impossible to predict individual braking time based only on radiographic findings or number of weeks after surgery. It would be ideal to test braking performance individually in a driving simulator, which is neither practical nor available in every case.

Thus, the aim of this study is to investigate whether a simple regression model to estimate braking performance for individual patients can be developed. Therefore, the dimensions with the highest correlation (sex, age, Hau's step test, Hip disability/Knee injury and osteoarthritis outcome score (H/KOOS), and pain scale) were included. We further analyzed dimensions of body height, body weight, body mass index, the timed up and go test, the ruler drop test, Marmon's single-step test, sports activities per week, driving license possession, kilometers driven, Kellgren-Lawrence grade, and the numeric pain rating scale.

Materials and Methods

A cross-sectional study was performed with patients having OA of either the knee or the hip or having undergone a total hip or knee replacement. All subjects were tested during consultation or before a planned hip or knee replacement. Recruitment time was from October 2014 to May 2015. The sample size was calculated after performing a pilot study with 10 patients. A study with the same patient cohort measuring braking performance with a small electrical device (reaction timer) has already been published (15). Full departmental, institutional, and local ethical committee approvals were obtained before commencement of the study. Written informed consent was received from all subjects before participation.

Participants

Patients were randomly asked to participate in the study. Inclusion criteria were: age between 18 and 85 years, possession of a valid driving license, and OA of the right or left hip/knee or hip/knee replacement. Exclusion criteria were: a recent stroke or heart attack within the previous six months, use of a walking frame, cardiac insufficiency (NYHA 3-4), a peripheral sensorimotor deficit with a grade of <3/5 on the Medical Research Scale for muscle strength, recent fractures, systemic or metastasized cancer, and drug intake known to affect reaction time.

Demographic data and questionnaires

Included demographic data were patient age, height, sex, body weight, smoking, years of driving experience, yearly kilometers driven, weekly sports activities (in hours), drug intake, and comorbidities (e.g., diabetes, polyneuropathy). Subjective data recorded were the numeric pain rating scale (NRS) under physical strain and the H/KOOS (16, 17). Further, the Kellgren-Lawrence classification system for osteoarthritis of the hip joint was used to identify the severity of the arthritis by grading radiographic images (18).

Testing of braking performance

The experimental setup was that used in previous studies (14). The measurement system was incorporated in a Volkswagen Polo-2 automobile to collect measurements under realistic ergonomic conditions. The accelerator and brake pedals were equipped with force transducers connected to a measurement amplifier. Incoming data were then sent to a registration module (Figure 1. a, b). A red light-emitting diode (LED) connected to the registration module was attached to the hood at the driver's eye level. All incoming data were processed by a custom-made computer program (Figure 1c).

This experimental setup can measure the different components of brake response time (BRT) in seconds—reaction time (RT) plus foot transfer time (FTT)—and brake force (BF) in Newtons. With respect to decision-making and whether adequate braking can be performed, BRT is considered the essential dimension (14, 19-21).

Each participant was asked to adjust the driver's seat to their usual driving position and to wear footwear that they normally used while driving. Subjects were asked to push the accelerator continually, thereby starting the registration process. Within a random interval of up to 10 s, the supervisor activated the red LED, which participants were instructed to consider the emergency signal upon which they needed to perform emergency braking.

RT was measured as the time elapsed between flashing of the LED and the beginning of decreased pressure on the accelerator. From this point on, FTT was measured to the beginning of increased pressure on the brake pedal. The maximum force with which the brake pedal can be depressed is defined as the braking force, which was additionally measured. Ten measurements were performed to obtain the gold standard of individual braking time. In addition, 3 practice trials were performed before experimental registration. The tested parameters were "expected", and the signal given was clear. No decision-making process about whether to steer or to brake was required, and no cognitive load distracted the participants. Although this does

HIGHLIGHTS

- Comparison of braking times in a brake simulator with demographic data, various clinical tests and pain surveys.
- Development of a multiple linear regression model to estimate the BRT in everyday medical practice.
- Regression model can give a first estimate of braking performance but does not allow a forensic statement.

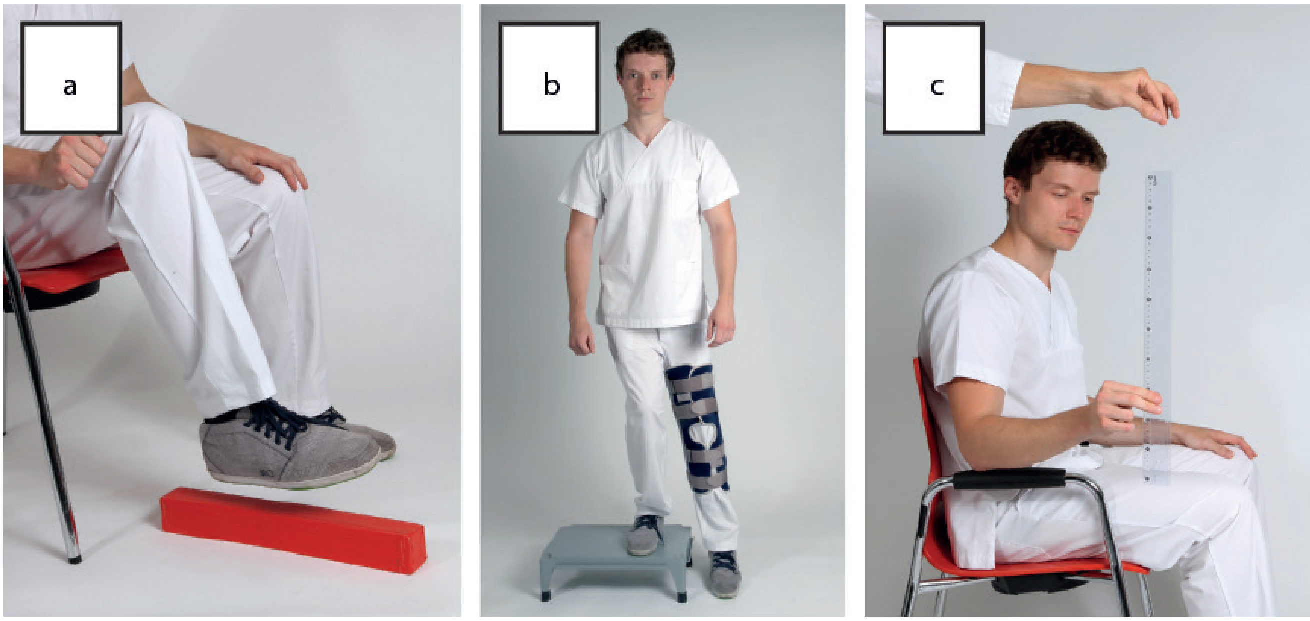

Figure 2. a-c. Experimental clinical tests: (a) The step test according to Hau (22) was performed with the patient seated and both hips and knees positioned at 90° flexion. An oblong wooden cube measuring 5x5x30 cm was placed medially to the patient's right foot. The foot was lifted across the cube and alternately placed alongside either side of the box without touching it; the heel always firmly planted on the ground. Tiptoeing was not allowed. The repetitions achieved in 10 s were recorded. (b) For Marmon's single-step test (23), the patient's left leg was fitted with a knee-immobilizing orthosis to disable it. The right leg stood on a 15-cm high stool. The patient was instructed to bring the left heel onto the floor and then move it back onto the stool. This setup was repeated 10 times, and the time was recorded. (c) The ruler drop test (24, 25) calculated reaction time as the distance at which the ruler falls from its release (the lower end of it between thumb and index finger of the patient) until the patient grasps it with their fingers. 5 measurements were performed

not represent an actual driving context, the setup minimizes confounding factors and concentrates on measuring the musculoskeletal influence on braking performance.

Clinical testing

Clinical tests performed by the participants were Hau's step test (22), Marmon's single-step test (23), a ruler drop test (24, 25), and the timed up and go test (26). These tests were chosen according to examples in previous literature that included both components—RT and FTT. All tests had to be simple and easy to perform, without the need for costly equipment. In Hau's step test (22) (Figure 2a), patients were seated at a height leading to 90° knee and hip flexion. An oblong wooden cube measuring 5´5´30 cm was placed medially to the patient's right foot. The participant was instructed to lift the foot across the cube and place it alternately alongside either side of the box without touching it. The number of crossings in 10 s was recorded.

For Marmon's single-step test (Figure 2b), patients wore a standard knee-immobilizing orthosis on the left leg to disable knee function (23). With the right foot standing on a 15-cm block, patients were asked to bring the heel of the left leg to the floor and then back to the block 10 times, as quickly as possible, and the elapsed time (in seconds) was measured. Due to the painful conditions of these patients, the originally planned 20 repetitions were reduced to 10 for this study.

For the ruler drop test (Figure 2c), a 40-cm plastic ruler was held by the examiner at one end with the other end hanging between the open opposing index and thumb of the participant sitting on a chair with the forearm lying on the armrest so that a small gap remained between the two fingers and the ruler on each side. At a random interval, the ruler was dropped by the examiner, and subjects had to close their fingers to catch the ruler as quickly as possible (24, 25). With negligible movement time, RT is calculated as follows: t =; t = time, d = distance in centimeters that passed through the fingers, and g = 9.81 m/s^2. This procedure was repeated 5 times.

For the timed up and go test, the patient sat on a standard armchair (seat height: 46 cm), with their back against the backrest and arms resting on the chair's arms (26). Any assistive device used for walking was placed nearby. Upon the signal to begin measuring, the patient had to stand up and walk to a line at a 3-m distance, turn around at the line, walk back to the chair, and sit down. The elapsed time (in seconds) until the patient's buttocks touched the seat again was measured.

Statistical analysis

Statistical evaluation was performed using IBM Statistical Package for Social Sciences version 21 (IBM SPSS Corp.; Armonk, NY, USA) and R (R Foundation for Statistical Computing).

Normality was determined by histograms. Data are reported as means (standard deviation). Testing was performed by t-test and chi-square test for gender with a two-tailed significance level of p=0.05. Correlation analyses were carried out by Kendall tau rank correlation. Graphic display of the reported data was performed by boxplots and scatterplots. Patients with missing data were excluded from the study. Following correlational analysis, a multiple linear regression was performed to predict mean BRT by age, sex, H/KOOS pain, and Hau's step test. These predictor variables contributed significantly to the prediction. BRT increases linearly in female sex, with increasing age, and decreasing values of H/KOOS pain and Hau's step test. A formula is provided to easily predict BRT from these values, and the corresponding 95% confidence intervals are reported. For more details regarding the statistical procedure underlying the regression model calculation, see appendix 1.

Results

A total of 162 patients were included in the study: in the hip group, 64 had hip OA and 37 had total hip arthroplasty, and in the knee group, 45 had knee OA and 16 had total knee arthroplasty. All patients completed the study. There were more women (n=90) than men (n=72) in both groups, with no significant difference in sex ratio (p=0.180) in the subgroups. The mean age was 64 (12.8) years, with no significant difference between the knee and hip groups (p=0.482). With similar body heights, the knee group was about 5 kg heavier than the hip

Table 1. Demographic data

Parameter	Study group (n=162)	Hip group (n=101)	Knee group (n=61)	p
Age [y]	64 (12.7)	64 (12.3)	63 (13.5)	0.482°
Men	72	49	23	
Women	90	52	38	0.180*
Body height [m]	1.69 (9.3)	1.69 (10.1)	1.70 (7.9)	0.337°
Body weight [kg]	83 (17.2)	81 (16.2)	86 (18.5)	0.048°
Body mass index [kg/m²]	29 (5.3)	28 (4.7)	30 (29.8)	0.069°

Demographic characteristics presented as mean and standard deviation. *Pearson Chi-square and °t-test for independent samples comparing the hip and knee group.

Table 2. Correlation of braking performance and regression model factors

	Brake response time [ms]		
Parameter	Study group (n=162)	Hip group (n=101)	Knee group (n=61)
Age [y]	τ=0.176, p=0.001	τ=0.073, p=0.290	τ=0.359, p<0.001
Sex	τ=0.361, p<0.001	τ=0.382, p<0.001	τ=0.331, p=0.002
Hau's step test [n]	τ=-0.345, p<0.001	τ=-0.318, p<0.001	τ=-0.324, p<0.001
H/KOOS Pain	τ=-0.265, p<0.001	τ=-0.242, p<0.001	τ=-0.290, p=0.001

n=sample size, τ=Kendall's tau, p=significance

Table 3. Additional clinical testing and braking performance

	Brake response time [ms]					
Parameter	Study group		Hip group		Knee group	
Body height [m]	n=162, p<0.001	τ=-0.270,	n=101, p<0.001	τ=-0.301,	n=61, p<0.005	τ=-0.250,
Body weight [kg]	n=162, p=0.335	τ=-0.052,	n=101, p=0.020	τ=-0.159,	n=61, p<0.350	τ=0.083,
Body mass index [kg/m2]	n=162, p=0.038	τ=0.110,	n=101, p=0.444	τ=0.052,	n=61, p=0.033	τ=0.188,
Timed Up and Go test [s]	n=162, p<0.001	τ=0.337,	n=101, p<0.001	τ=0.332,	n=61, p<0.001	τ=0.351,
Ruler drop test [m]	n=162, p<0.001	τ=0.298,	n=101, p<0.001	τ=0.278,	n=61, p<0.001	τ=0.349,
Marmon's single-step test [s]	n=151, p<0.001	τ=0.346,	n=90, p<0.001	τ=0.310,	n=61, p<0.001	τ=0.423,
Sports activities per week [h]	n=162, p=0.033	τ=-0.127,	n=101, p=0.406	τ=-0.063,	n=61, p=0.025	τ=-0.219,
Driving licence possession [y]	n=162, p=0.121	τ=0.083,	n=101, p=0.430	τ=-0.054,	n=61, p=0.001	τ=0.302,
Driven kilometres [km]	n=150, p<0.001	τ=-0.279,	n=89, p=0.009	τ=-0.195,	n=61, p<0.001	τ=-0.360,
Kellgren-Lawrence grade	n=87, p=0.672	τ=0.036,	n=54, p=0.119	τ=0.166,	n=33, p=0.231	τ=-0.176,
Numeric Pain Rating Scale	n=162, p<0.001	τ=0.267,	n=101, p<0.001	τ=0.295,	n=61, p=0.063	τ=0.185,

n=sample size, τ=Kendall's tau, p=significance

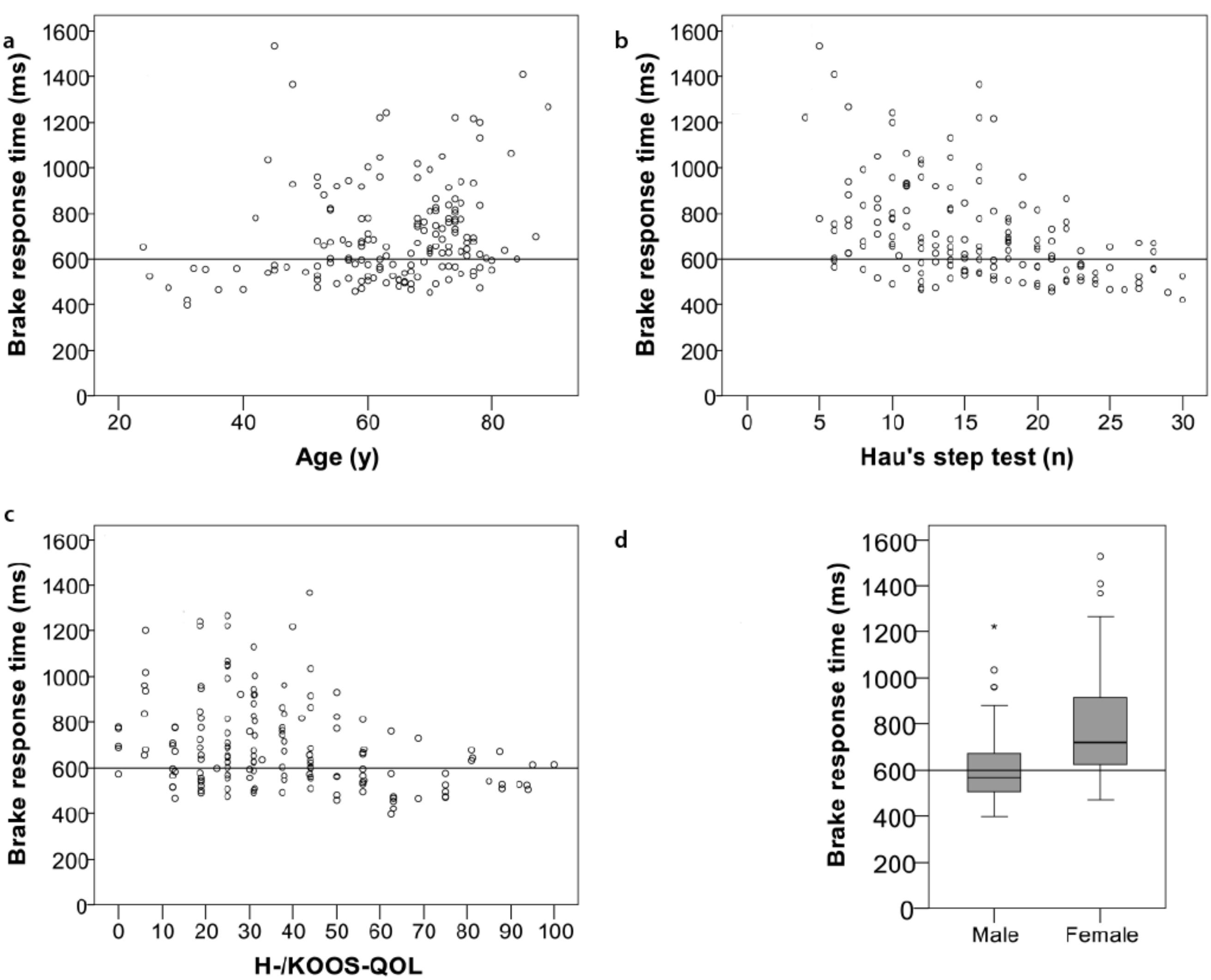

Figure 3. a-d. Dimensions used in the regression model for BRT: Scatterplots for (a) age, (b) Hau's step test, and (c) KOOS pain. (d) Boxplots showing the difference in BRT between male and female participants

Table 4. Regression model

	Beta (standard error)	95% confidence interval Lower (2.5 %)	Upper (97.5%)	p
Sex (female)	119.2 (26.8)	66.1	172.2	<0.001***
Age	3.0 (1.2)	0.7	5.3	<0.05*
Hau's step test	-8.8 (2.5)	-13.7	-3.8	<0.001***
H/KOOS Pain	-1.3 (0.6)	-2.5	-0.1	<0.05*

Residual standard error: 158.4, adjusted R^2: 0.31, F(4,140)=16.8, ***p<0.001, *p<0.05

group (p=0.048) (Table 1). BF appeared to be no problem in the tested groups, with only 2 subjects pressing the brake pedal with a force below the suggested limit of 100 N (11, 12). A total of 99 subjects (61%) exceeded the suggested limit for BRT of 600 ms for our brake simulator. Although the BRT was higher in the group of patients with knee pathology (694 [397–1,366] ms) than that in hip patients (628 [422-1,532] ms), this difference was not statistically significant (p=0.100) (appendix 1).

BRT was then correlated with results obtained from the clinical tests, questionnaires, and subject-related data to identify key factors suitable for creating a regression model (Tables 2 and 3, appendix 2). The correlation with age was significant for the knee group (τ=0.359, p<0.001), whereas it played no major role in patients with hip OA or arthroplasty (τ=0.073, p=0.290). Men performed significantly better than women, with mean BRTs of 615 (165) and 775 (221) ms, respectively (p<0.001). This effect is also manifested in a seeming relationship between body height and BRT (both sexes τ=–0.270, p<0.001; men: τ=–0.034, p=0.675; women: τ=–0.140, p=0.057). Both step tests showed significant, moderate correlations with BRT (Hau's step test: τ=–0.345, p < 0.001; Marmon's single-step test: τ=0.346, p<0.001). H/KOOS pain (τ=–0.265, p<0.001) and NRS (τ=0.267, p<0.001) also correlated weakly with BRT.

In the final linear regression model, which was fitted to the results of n=145 patients with complete datasets, the dimensions, sex, age, Hau's step test, and H/KOOS pain were included (Table 4, Figure 3). We, therefore, suggest the following formula: BRT_{est} = 634.8-(8.8´Hau)+119.2 (for women)+(3.0´age)-(1.3´H/KOOS pain).

The regression model achieves a multiple R^2 of 0.32 (R^2_{adj} = 0.31) and thus accounts for only 32% of the overall variance observed in BRT. The model leaves a residual standard error (i.e., SD of the residuals) of 158.4 ms, and it is superior to a model without predictors, F (4.140)=16.8, p<0.001. For more details regarding the regression model calculation, see appendices file 3 and 4.

Discussion

The aim of this study is to evaluate whether a simple model can be generated to estimate the expected value of BRT in patients with OA or joint arthroplasty of the knee or hip.

As observed in earlier studies (14, 27, 28), patients with left-sided pathology presented impaired braking values, and the difference between the left and right sides was not large enough to include the side factor in the regression model. Sex, in contrast, had a strong impact on the results. In line with the literature, the observed difference between women and men can largely be attributed to foot transfer time (FTT) (mean difference: 127 ms), whereas reaction time (RT) (mean difference: 32 ms) is almost identical (29). It can be inferred that these differences are attributable to the musculoskeletal differences between women and men. This also applies to age and FTT.

With respect to clinical parameters, previous studies have already described different correlations with BRT. Liebensteiner et al. described moderate correlations between reported values on the Visual Analogue Scale and BRT in patients before and after lumbar fusion (30). Similar results on the Visual Analogue Scale were described by Thaler et al. for left-sided radiculopathy and by Al-khayer et al. for patients with leg pain after selective nerve root block (31, 32). Concerning knee pathologies, Hau et al. published 2 studies in 2000 in which they analyzed the relationship of BRT with a step test as well as with a standing test before and after knee arthroscopy and anterior cruciate ligament reconstruction (22, 33). Moderate correlations were found in all cases (step test: r=–0.45/–0.79; standing test: r=–0.35/–0.70; all p<0.001). Interestingly, all clinical correlations tested strongly exceeded the relationship of BRT and radiographic OA grading (n=87, τ=0.036, p=0.672), a method usually used to illustrate the severity of the condition (34).

When interpreting such correlations, it must be pointed out that the gold standard of testing in a brake simulator already shows much variability (mean range of 336 [252] ms over the 10 measurements in our study). A regression model must take these weaknesses into account. The same applies, however, to time-based recommendations: In a previous study in our department, perioperative driving performance was analyzed in n=40 patients receiving total knee arthroplasty (10). It was concluded that driving should be possible 6 weeks after TKA. Due to high interindividual variability, however, it was clearly stated that a general recommendation can hardly be formulated as a function of time. Indeed, the measured range for BRT was 400–906 ms preoperatively with an interquartile range (IQR) of 170 ms. At 6 weeks postoperatively, these values ranged from 375 to 856 (IQR 481) ms; at 3 months postoperatively, they ranged from 378 to 790 (IQR 142); and at 1 year postoperatively, they still ranged from 426 to 709 (IQR 104) ms. With respect to TKA or THA, other studies found similar or even greater ranges of up to 700 ms (13, 35, 36). It is noteworthy that these ranges also approximately match the 95% confidence interval that can be generated when using the regression model generated in this study. It is clear that both methods, a fixed time-point or pathologic condition-based recommendation and a regression model based on clinical testing, cannot offer sufficiently precise information on the actual braking performance of the individual. It is thus essential to be aware of relevant risk factors that we describe in our study to sensitize patients to their possibly impaired driving capability, and in case of doubt, motivate them to perform proper testing at the corresponding institutions.

The main strengths of this study are the standardized methodology and the broad testing approach. The testing equipment has high measurement precision, and the large sample size allows proper statistical analyses. As we did not register the number of patients that were ineligible for the study, we clearly stated the exclusion and inclusion criteria. Therefore, the reader can verify whether our data presented herein can be generalized to their local conditions. Although braking performance represents only one aspect of fitness to drive, it is the most important musculoskeletal parameter from an orthopedic point of view. In a follow-up study to further improve the regression model, repeating Hau's step test measurements might increase prediction accuracy because of the strong impact of this test on the final value. As we measured patients with both OA and arthroplasty of the knee or hip in the order they appeared in our consultation, the composition of the patient collective with respect to joint replacement versus OA is the result of the composition of patients in our consultation.

In conclusion, our evaluated regression model offers an uncertainty comparable to the one based on a fixed time period after surgery or a defined pathologic condition. Taking the available data in the literature into account, we advise caution when formulating a real-time- or condition-based recommendation. Rather, we suggest being aware of risk factors that might lead to impaired BRT to sensitize patients to their impaired ability to drive. Such factors associated with increased BRT are older age, female sex, impaired musculoskeletal function, as tested in Hau's step test, and high levels of pain.

Ethics Committee Approval: Ethics committee approval was received for this study from the Ethics Committee of the University of Tübingen (619/2013BO2; 503/2014BO2).

Informed Consent: Written informed consent was obtained from the participants included in the study.

Acknowledgments: We thank Thomas Müller (FRG) for taking the photographs of the drive simulator, and Barbara Every, ELS, of BioMedical Editor, for English language editing.

Author Contributions: Concept - U.K.H., M.B.; Design - F.B.; Supervision - I.I.; Materials - J.R., M.F.; Data Collection and/or Processing - M.B., J.R.; Analysis and/or Interpretation - U.K.H.., M.B., F.B.; Literature Search - M.F.; Writing Manuscript - M.B, U.K.H.; Critical Review - M.F., F.B., U.K.H.

Conflict of Interest: The authors have no conflicts of interest to declare.
Financial Disclosure: This project was supported by the AKF-programme of the University of Tübingen (AKF - angewandte klinische Forschung/applied clinical research) (grant number AKF-280-1-0).

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Appendices

Appendix 1. Regression model calculation of BRT

In the final linear regression model, which was fitted to the results of *N*=145 patients with complete datasets, the dimensions sex, age, Hau's step test and H/KOOS Pain were included (Appendix 3 and 4). All four predictors contribute significantly to the prediction of BRT.

The regression model achieves a multiple R^2 of .32 (R^2_{adj}=.31) and thus accounts for only 32 % of the overall variance in observed BRT. The model leaves a residual standard error (i.e., *SD* of the residuals) of 158.4 ms, and it is superior to a model without predictors, F (4.140)=16.8, p<0.001.

The relative weights [30] of the predictors in this model amount to 33.5%, 36.0%, 11.3% and 19.2% of the explained variance for Hau's step test, sex, age, and H/KOOS pain, respectively. Therefore, the strongest predictors of BRT are sex and Hau's step test, which taken together are responsible for 69.5% of the variance that can be explained by the model. In comparison, H/KOOS pain and age contribute less strongly to the prediction.

Finally, multicollinearity was tested by means of variance inflation factors (VIFs). VIFs for this model are 1.27, 1.03, 1.00, and 1.26 for Hau's step test, sex, age, and H/KOOS pain, respectively. Since in all cases the general rule < 2 is satisfied, no problems with multicollinearity are indicated by this analysis.

To estimate BRT, we therefore suggest the following formula (cf. Appendix 4):

BRT_{est}=634.8 - (8.8´Hau) + 119.2 (for women) + (3.0´age) - (1.3´H/KOOS Pain)

For an 81-year-old female subject with Hau=28 and H/KOOS Pain=81, BRT_{est} would be as follows:

BRT_{est}=634.8 - (8.8´28) + 119.2 + (3.0´75) - (1.3´81)=627.2 ms with a 95% confidence interval of [307-951] ms. In this case, the confidence interval would cover a range of about 644 ms. At 100 km/h, this span represents a difference in total stopping distance of 17.8 m. The total stopping distance increase by a BRT of 627.2 ms, exceeding the suggested limit for our experimental setting of 600 ms, would be 0.75 m. Examples from the tested groups are shown in Appendix 4.

Statistical analysis of the regression model

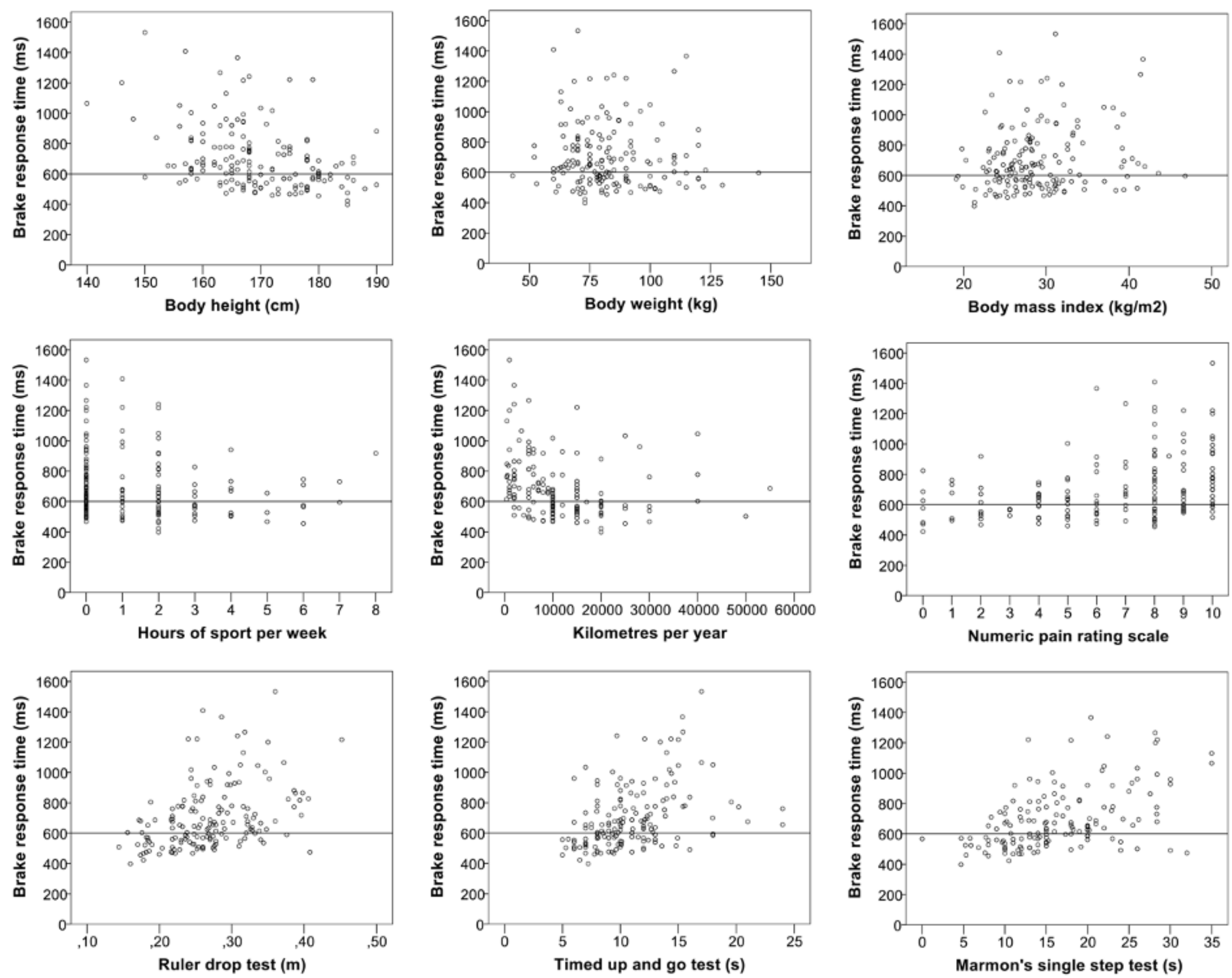
Stepwise multiple linear OLS regression, employing the stepAIC (Akaike Information Criterion) function of the R library MASS, was conducted. The Akaike Information Criterion was used as a measure of relative quality to evaluate the models' fits in the stepwise regression procedure. Specifically, forward and backward regression was performed on a set of potential predictor variables chosen from their degree of correlation with BRT, but also from their practicability in everyday practice. These included variables were Hau's step test, BMI, Sex, age, the pain dimension of the H/KOOS, ruler test, timed-up-and-go-test, and the numeric pain rating scale. Marmon's single-step test was not included in this regression, since results were comparable with those from Hau's step test and we deemed the latter easier to perform and less hazardous. Moreover, 11 patients in the hip group did not complete Marmon's single-step test because of severe pain during the procedure. The dimensions other than pain from the H/KOOS also were excluded since they showed a less relevant correlation with BRT. BMI was preferred as potential predictor over height and weight. Multicollinearity of the model parameters was assessed through their variance inflation factors.

The linear model resulting from the stepwise regression included Hau's step test, sex, age, H/KOOS pain, and the ruler test as predictor variables. However, since both age and the ruler test only contributed marginally (p<0.10) to the prediction of brake response time and were positively correlated, *r*(142)=.27, p<0.001, the ruler test was dropped in favour of age as predictor of BRT.

Appendix 2. Study group and braking performance

Parameter	Study group (n=162)	Hip group (n=101)	Knee group (n=61)	p
Reaction time (ms)	240 (136-630)	232 (152-630)	265 (136-493)	0.006
Foot transfer time (ms)	402 (213-1052)	399 (251-1052)	411 (213-922)	0.373
Brake response time (ms)	652 (397-1532)	628 (422-1532)	694 (397-1366)	0.100
Brake force (N)	303 (82-1189)	300 (82-1149)	315 (99-1189)	0.209

P-value comparing the hip and knee group. Significant p-value is denoted in bold.



Appendix 3. Scatterplots of the other parameters analysed for correlation with braking performance

Appendix 4. Calculated brake response time and braking performance in the simulator

		Regression model						
Patient		- 8.8 x Hau	+119.2 for women	+3.0 x age	- 1.3 x H/KOOS Pain	Calculated BRT	95% prediction interval	Actual BRT
1		(26) 228.8	0	(36) 108.0	(68.75) 89.4	425.8	101-751	467
2	634.7	(28) 246.4	119.2	(75) 225	(81) 105.3	629.3	307-951	632
3		(9) 79.2	119.2	(74) 222.0	(44.44) 57.8	840.7	523-1157	864

Values obtained from patients are denoted in parentheses