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BASIC SCIENCE

Doctor, when can I drive?—the range of elbow motion while driving a car

David Latz, MD[a], Erik Schiffner, MD[a,*], Johannes Schneppendahl, MD, PhD[a], Falk Hilsmann[a], Lars Fabian Seiler[a], Pascal Jungbluth, MD, Prof.[a], Robert Alexander Kaufmann, MD[b], Joachim Windolf, MD, Prof.[a], Sebastian Viktor Gehrmann, MD, Prof.[a]

[a]*Department of Trauma and Hand Surgery, University Hospital, Düsseldorf, Germany*
[b]*Department of Orthopaedic Surgery, University Hospital, Pittsburgh, PA, USA*

Background: Immobilization of the upper extremity after an acute injury or postoperatively affects an individual's ability to safely operate a motor vehicle. The elbow is particularly sensitive to immobilization, with subsequent stiffness leading to functional limitations. Most activities of daily living are successfully achieved within a "functional arc" of elbow motion between 30° and 130° of flexion. No objective guidelines exist regarding the range of motion needed to safely operate a vehicle. In this study, we measured the range of motion of right and left elbows while driving a manual-transmission car.
Materials and methods: Using electro-goniometers, we measured the flexion and extension, as well as pronation and supination, of the right and left elbows in 20 healthy, right hand–dominant subjects while driving a car. These measurements were recorded on (1) city streets, (2) country roads, and (3) highways.
Results: For city streets, the range of motion in terms of flexion and pronation/supination was 15°-105° and 0°-45°/0°-35°, respectively, for the right elbow and 20°-95° and 0°-45°/0°-40°, respectively, for the left. For country roads, it was 10°-100° and 0°-40°/0°-35°, respectively, for the right elbow and 20°-95° and 0°-30°/0°-30°, respectively, for the left. For highways, it was 5°-100° and 0°-40°/0°-35°, respectively, for the right elbow and 20°-90° and 0°-30°/0°-25°, respectively, for the left. Mean pronation was significantly higher for the right elbow ($P < .01$).
Conclusion: This study describes the range of elbow motion identified to drive a car with a manual transmission and a left-sided steering wheel. Mean pronation of the right elbow is significantly higher than that of the left. Further studies are needed to investigate the relevance of movement restrictions as they relate to handedness, steering-wheel side, and driving impairment.
Level of evidence: Basic Science Study; Kinesiology

Keywords: Driving fitness; elbow; forensic medicine; range of motion; traffic medicine; trauma surgery

Driving requires that the elbow move through a range of motion (ROM) that allows the driver to turn a steering wheel and, in certain cases, actuate a manual transmission. Loss of elbow motion, such as may occur after injury[12,13,15,28] or because of immobilization, affects the ability to safely operate a motor vehicle. The ROM of the elbow significantly influences the

The ethics committee of the Medical Faculty of Heinrich Heine University Duesseldorf (No. 3362) approved this study.

*Reprint requests: Erik Schiffner, MD, Department of Trauma and Hand Surgery, University Hospital, Moorenstrasse 5, Düsseldorf 40225, Germany.
E-mail address: erik.schiffner@med.uni-duesseldorf.de (E. Schiffner).

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capacity of the upper extremity as a functional unit (shoulder, elbow, and wrist),[3,14,23,24,29] and a loss of elbow ROM is less well tolerated than motion loss in adjacent joints.[22] Thus, injuries to the elbow or restrictions of elbow ROM easily affect driving capabilities. Physicians are frequently charged with determining whether their patients are permitted to drive, and they may be held liable in the event of an accident.[16] Despite this, few guidelines exist that quantify when driving may be allowed. Patients often decide based on subjective perceptions of their own capabilities.[5] Previous studies have suggested that most activities of daily living can be accomplished with 100° of elbow flexion (30° to 130°).[14] Objective parameters regarding the necessary elbow ROM for driving a car are lacking[6] yet do exist for the wrist.[11] The aim of this study was to measure the elbow ROM used when driving a car with a left-sided steering wheel and a manual transmission on (1) city streets, (2) country roads, and (3) highways.

Materials and methods

This was an experimental study. A total of 20 healthy, right-handed[18] subjects (10 women and 10 men) without a history of upper-extremity trauma or recent immobilization participated in this study. Subject ages varied between 23 and 36 years, with a mean of 29 ± 3 years. All participants were required to possess a valid driver's license and own their own vehicle, which they drove more than 5000 km/yr. All cars had a left-sided steering wheel. The exclusion criteria were pregnancy, musculoskeletal or systemic diseases, diseases of the central or peripheral nervous system, psychiatric disorders, and chronic drug or alcohol abuse. Each subject completed a standardized questionnaire, and written informed consent was obtained prior to subjects' participation.

To characterize the ROM of the elbow, we used an electrogoniometer (Twin Axis goniometer, type SG 65; Biometrics Ltd, Newport, UK) and torsiometer (Single Axis torsiometer, type Q 150; Biometrics Ltd) that recorded flexion-extension and pronation-supination, respectively. Electro-goniometers measure flexion-extension based on strain changes along the length of a wire between 2 end blocks. The design measures only angular and not linear movements. Torsiometers measure pronation-supination based on relative axial rotation between 2 end blocks. If the torsiometer is bent, the output remains constant. The goniometer was attached with double-sided medical adhesive tape to the lateral aspect of the elbow, and the torsiometer was attached to the ulnar aspect of the neutral-positioned forearm (Fig. 1, *a*).

To determine each participant's valid and reproducible full elbow ROM, we instructed the subjects to perform 10 repetitions of maximum flexion-extension and pronation-supination for each elbow, and these values were compared with an external goniometer. Differences greater than ±10° were excluded. After the individual maximum ROM was determined, subjects were fitted while in their own car, which had a steering wheel on the left side and a manual transmission. A uniform sitting position was carefully established for each participant.[1] We instructed the subjects to drive 3 predetermined routes twice each—(1) city streets, (2) country roads, and (3) highways (Fig. 1, *b*)—and not to exceed maximum speeds of 30, 80, and 120 km/h for city streets, country roads, and highways, respectively. All subjects drove on the right side of the road, and the order of traveled routes was randomized for each subject. During the procedure, motion data of the joints were continuously measured (50/s) and transmitted to a mobile computer system.

We processed raw data from the electro-goniometer and torsiometer using Datalog analysis software (Biometrics Ltd) and a customized MATLAB program (The MathWorks, Natick, MA, USA). The mean and standard deviation of flexion-extension and pronation-supination measurements were calculated for every road type. For statistical analysis, the SPSS software program (version 25; IBM, Armonk, NY, USA) performed a multivariate analysis of variance (MANOVA) with the factors road type (city, country, and highway) and arm side (right and left elbow) followed by a subsequent univariate analysis that was performed for data with a normal distribution to assess for statistical differences. P values were corrected for multiple testing using the Bonferroni test. $P < .05$ was assumed to be statistically significant. In addition, we ranked the relative probabilities of different elbow positions and displayed the findings as a histogram. Kolmogorov-Smirnov tests were used to assess for normal distributions.

Results

The Edinburgh Handedness Inventory[18] indicated that all participants were right handed.

Extension-flexion

The individual maximum and minimum extension-flexion of the elbow and the mean extension-flexion of the elbow while driving on different road types are shown in Table I. Descriptive statistics of the probability of elbow position in extension-flexion are shown in Table II and Figure 2.

A Kolmogorov-Smirnov test showed no normal distribution for elbow extension-flexion overall ($P < .001$) but showed a normal distribution for mean extension-flexion ($P = .08$). The MANOVA showed no significant main effect for road type (Wilks $\Lambda = 0.98$; $F_{4,226} = 0.49$; $P = .75$) or interactions (Wilks $\Lambda = 0.99$; $F_{4,226} = 0.27$; $P = .90$) but showed a significant main effect for arm side (Wilks $\Lambda = 0.91$; $F_{2,113} = 5.74$; $P = .004$). The subsequent univariate analysis showed no significant difference in extension-flexion for the right elbow compared with the left elbow for all road types ($F_{1,238.97} = 0.80$; $P = .37$).

Pronation-supination

The individual maximum and minimum pronation-supination of the elbow and the mean pronation-supination of the elbow

Table I Individual maximum and minimum extension-flexion of elbow and mean extension-flexion of elbow (± standard deviation) while driving different road types

	ROM, °			
	Maximum extension/flexion	Mean flexion while driving		
		City	Country	Highway
Right elbow	0-7/0-127	59 ± 16	55 ± 18	54 ± 18
Left elbow	0-8/0-127	56 ± 15	52 ± 18	51 ± 18

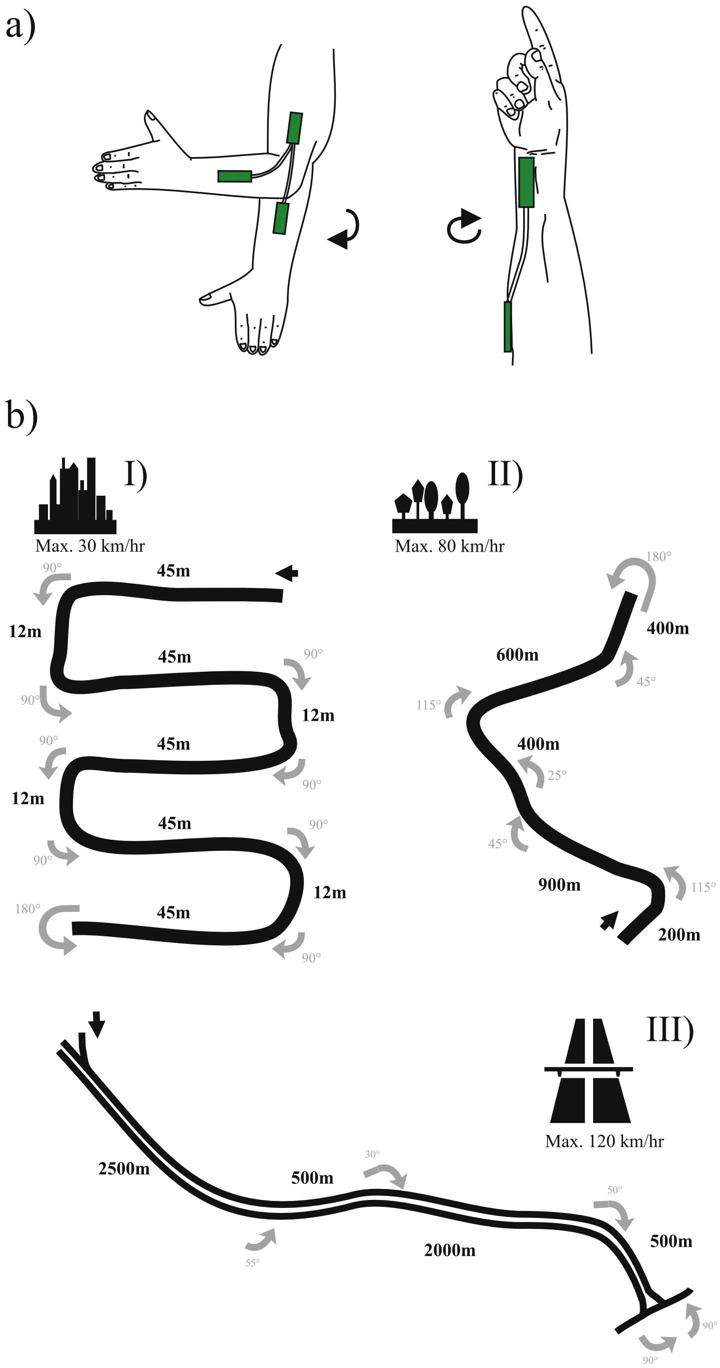

Figure 1 **(a)** The goniometer was attached to the lateral aspect of the elbow, and the torsiometer was attached to the ulnar aspect of the forearm in neutral position. **(b)** Schema of routes: (I) city streets, (II) country roads, and (III) highway. *Max*, maximum.

while driving on different road types are shown in Table III. Descriptive statistics of the probability of elbow position in pronation-supination are shown in Table IV and Figure 3.

A Kolmogorov-Smirnov test showed no normal distribution for elbow pronation-supination overall ($P < .001$) but showed a normal distribution for mean pronation-supination ($P = .2$). The MANOVA showed no significant main effect for road type (Wilks $\Lambda = 0.98$; $F_{4,226} = 0.49$; $P = .75$) or interactions (Wilks $\Lambda = 0.99$; $F_{4,226} = 0.27$; $P = .90$) but showed a significant main effect for arm side (Wilks $\Lambda = 0.91$; $F_{2,113} = 5.74$; $P = .004$). The subsequent univariate analysis showed higher mean pronation for the right elbow compared with the left elbow for all road types ($F_{1,1703.21} = 10.79$; $P = .001$).

Discussion

The elbow ROM that is required for performing most tasks is between 30° and 130° of flexion and between 50° of pro-

Table II Flexion of elbow in different location probabilities while driving different road types

	Flexion, °			
	Approximately 99%	Approximately 90%	Approximately 75%	Approximately 50%
Right elbow				
City	15-105	25-90	35-75	45-65
Country	10-100	25-85	35-75	30-50
Highway	5-100	30-90	30-70	35-50
Left elbow				
City	20-95	30-85	40-85	45-70
Country	20-95	30-85	30-75	30-55
Highway	20-90	25-80	25-70	30-40 and 65-75

Table III Individual maximum and minimum pronation-supination of elbow and mean pronation-supination of elbow while driving different road types

	ROM, °			
	Maximum pronation/ supination	Mean pronation while driving		
		City	Country	Highway
Right elbow	0-50/0-48	10 ± 12	12 ± 13	11 ± 13
Left elbow	0-52/0-47	6 ± 12	2 ± 12	2 ± 12

nation and 50° of supination.[14,24,29] When this motion is not achieved, a variety of treatment options may be considered.[9,13] To our knowledge, no investigation using goniometers has studied the elbow ROM required to drive a car. Rawal et al[19] defined the ROM of the upper extremity using a driving simulator and motion analysis with 13 cameras at different angles. In contrast, our study provides an ROM that was measured during actual driving conditions and in a manner that can be easily rechecked with an external goniometer. At present, there are no clear guidelines for advising patients regarding their potential driving limitations as they relate to elbow motion. The goal of this study was to demonstrate the mean ROM of the elbow while driving a car based on quantitative noninvasive measurements.

In this study, we identified the range of elbow motion that encompassed approximately 99% of those activities encountered by the right elbow during different driving conditions. This ROM lies between 15° and 105° of flexion and 0° and 45° of pronation/0° and 35° of supination for city roads; between 10° and 100° of flexion and 0° and 40° of pronation/0° and 35° of supination for country driving; and between 5° and 100° of flexion and 0° and 40° of pronation/0° and 35° of supination for highway driving. Mean pronation of the left elbow was significantly lower for all road types (Tables I-IV). All of the subjects were right handed and drove cars with a steering wheel on the left side mandating greater pronation by the right elbow during manipulation of the manual transmission. Our data demonstrate that the ROM of 5° to 105° in flexion-extension and 0°-45°/0°-35° in pronation/supination encompasses all the motion encountered by the right elbow and that the left elbow has fewer ROM needs. Furthermore, 50% of the right elbow ROM lay between 30° and 65° of flexion and between 0° and 25° of pronation. For the left elbow, 50% of the ROM lay between 30° and 75° of flexion and between 5° of supination and 25° of pronation (Tables II and IV).

Our results suggest that new guidelines for immobilization include a "driving arc of motion" that allows 5° to 105° in flexion and 0°-45°/0°-35° in pronation/supination. These findings correlate with recent studies that have warned against driving while immobilized in a long-arm cast,[26] whereas a short-arm cast with unrestricted elbow motion can be considered safer.[8] Different driver handedness as well as car features such as transmission type and steering-wheel location would potentially influence the ROM. In our study, the ROM of the elbow was characterized only in right-handed participants who did not exhibit discomfort or stiffness in adjacent

Table IV Pronation-supination of elbow in different location probabilities while driving different road types

	Pronation/supination, °			
	Approximately 99%	Approximately 90%	Approximately 75%	Approximately 50%
Right elbow				
City	0-45/0-35	0-35/0-20	0-25/0-15	0-20/0-0
Country	0-40/0-35	0-25/0-20	0-25/0-0	0-25/10-0
Highway	0-40/0-35	0-25/0-20	0-25/0-5	0-20/5-0
Left elbow				
City	0-45/0-40	0-30/0-20	0-30/0-10	0-25/0-5
Country	0-30/0-30	0-25/0-20	0-25/0-5	15-5/0-0
Highway	0-30/0-25	0-20/0-20	0-20/0-5	15-5/0-0

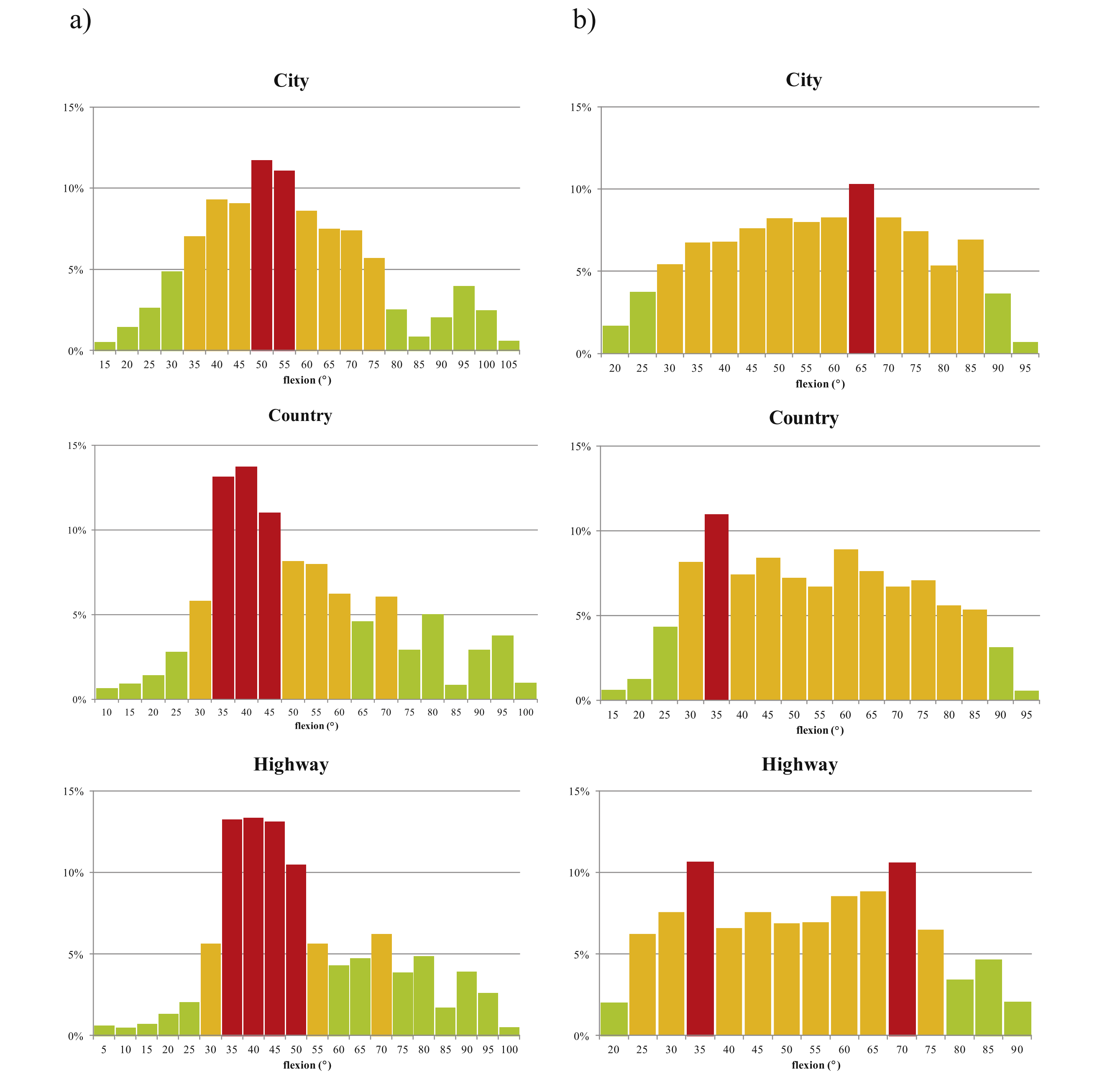

Figure 2 Histogram of range of motion in extension-flexion for right **(a)** and left **(b)** elbows (*green* indicates <5%; *yellow*, >5%; and *red*, >10%).

joints. Movement restriction of 1 joint as well as different handedness may influence the motion in adjacent joints.[7,30,31]

Further studies are needed to investigate the impact that elbow ROM restrictions may have on the actual ability to safely drive a car. Even though a certain ROM was observed, our results cannot suggest that a smaller motion capability renders vehicle operation unsafe. Furthermore, rare extreme movements, for example, turning the steering wheel quickly in a critical evasion maneuver or rapidly switching to another gear while overtaking a car, could be more important for safe driving than frequent average movements. Hence, it would be important to classify typical car driving maneuvers and examine their ROM requirement in addition to the necessary coordination, accuracy, speed, and reaction time in an additional study.

Our data do not provide insight into how movement quality such as coordination, reaction time, or accuracy influences driving capability, aspects that have been investigated in patients with Parkinson disease.[4,10,25] Furthermore, the influence that musculoskeletal discomfort has on driving capability may warrant exploration. Conditions such as medial or lateral epicondylitis,[27,32] olecranon bursitis,[20] impingement,[17,21] or arthritis[28] may affect driving capability and would benefit from further evaluation in randomized controlled studies. Such efforts may lead to an objective assessment of what constitutes "safe driving."

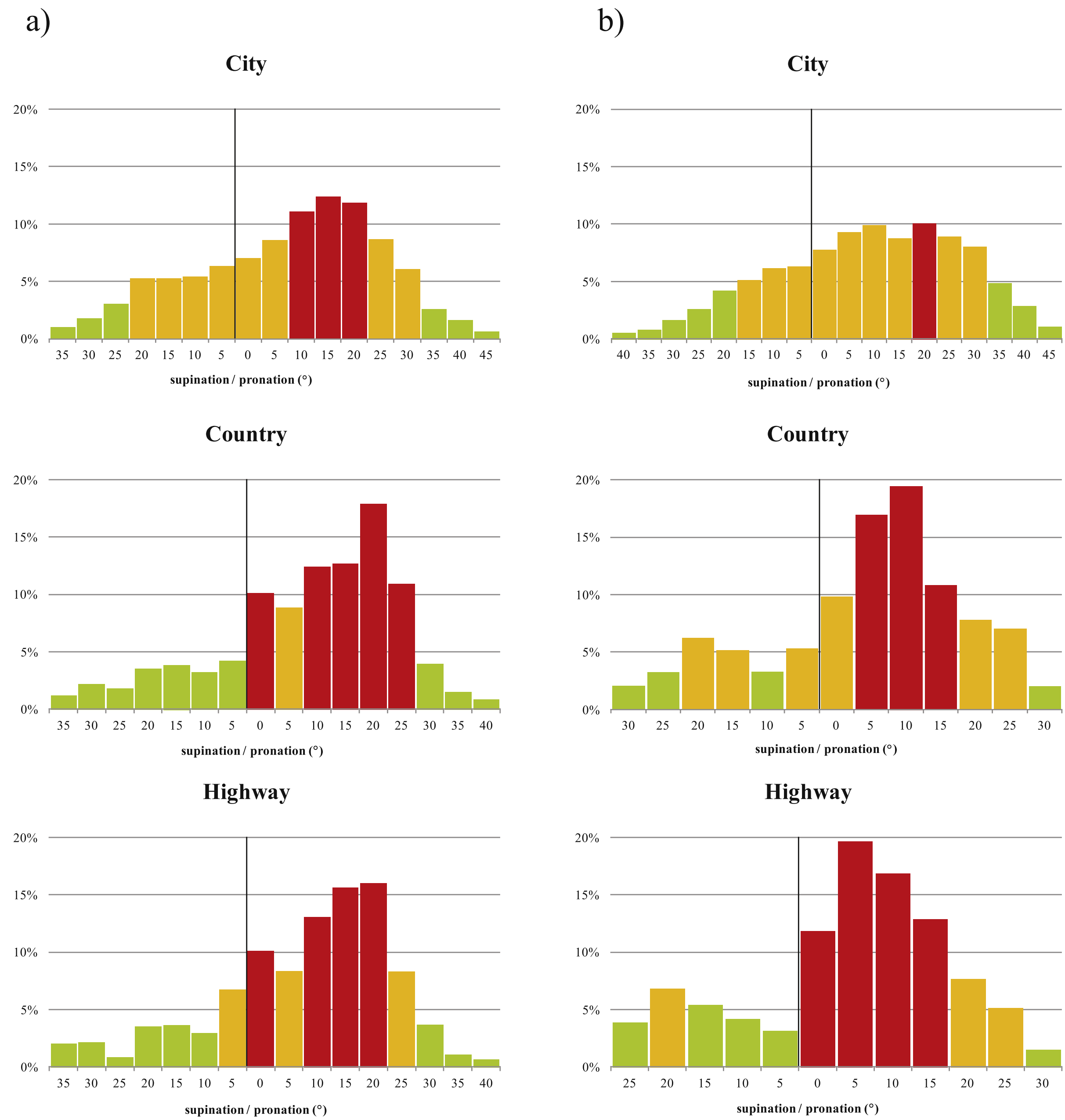

Figure 3 Histogram of range of motion in supination-pronation for right **(a)** and left **(b)** elbows (*green* indicates <5%; *yellow*, >5%; and *red*, >10%).

A major technical limitation of this study relates to matching the pronation-supination of the forearm with the torsiometer attached to the ulnar aspect of the forearm. When starting pronation or supination, no measurement errors are expected owing to soft tissue and skin movements. However, while achieving the maximum degree of pronation and supination, skin movements and relative movement of soft tissues lead to measurement errors larger than ±10°. To minimize that risk, double-sided adhesive tape was placed between the goniometer end blocks and the skin, a single adhesive tape was placed over the top of the end blocks, and bandages were fit over the whole sensor and interconnect lead. Still, our results for electro-goniometric maximum pronation/supination (approximately 0°-50°/0°-50°, Table III) could not reach the expected maximum ROM obtained using a goniometer (71°-84°),[2] indicating that our maximum values may not be valid. However, the mean ROM of pronation and supination while driving a car was smaller than 15° of pronation (Table III), and 90% of all pronation and supination activities lay between 0° and 35° and between 0° and 20°, respectively (Table IV), indicating that our subjects operated in a limited and, therefore in this study, valid ROM. Within this ROM, only minor measurement errors smaller than ±10° were expected, and therefore, our results should be valid.

On the basis of these results, further studies may quantify the upper extremity as a functional unit that consists of wrist, elbow, and shoulder motion. It may be of value to impart different simulated ROM limitations in any one joint and identify how other joints compensate for these, as well as how driving performance is affected. With these data, it may be possible to give experimentally and evidence-based recommendations for the timing and functional motion required to return to driving safely.

Conclusion

This study describes the range of elbow motion while driving a car on different road types. When driving a car with a left-sided steering wheel and a manual transmission on the right side, mean pronation of the right elbow is significantly higher than that of the left elbow. Our results further suggest that movement restrictions in pronation could possibly affect driving capability earlier than restricted supination. Further studies may shed light on the relationship between restricted elbow motion and handedness or different car settings.

Disclaimer

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