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Dependency of stabbing force on blade shape—Development of a measurement device and first results

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Abstract

Background: In court proceedings, forensic and biomechanical experts frequently have to estimate the stabbing forces necessary for a certain pattern of injury. Studies on this topic are rare.
Objective: Development and calibration of an experimental set-up for quantification of dynamic stabbing kinematics and forces.
Investigation of the influence of different shaped blades on stabbing forces.
Material and methods: We developed and calibrated a handle with an integrated force sensor and an accelerometer. Different blades can be attached to the handle. A total of 27 stabbings were performed by 1 volunteer at medium intensity and preferably reproducible stabbing velocities. We used three blades with different shapes. Gelatine served as tissue simulant. Maximum stabbing velocities were captured via two-dimensional high-speed videography.
Results: The force sensor calibration resulted in a nearly perfect linear regression. Stabbing velocities ranged between 2.7 and 5.0 m/s with stabbing forces between 54.8 and 129.3 N. Stabbing with the blunt blade resulted in significantly higher stabbing forces compared to pointed and serrated blades. A similar trend was observed for serrated versus pointed blades, but without statistical significance. A significant dependency of the stabbing velocity on stabbing force could only be proven for the serrated blade.
Conclusion: Blade shape and stabbing velocity are factors that can influence the resultant stabbing force. Reliable case evaluation needs the consideration of case-specific knives and circumstances.

Keywords
Stabbing · Experimental set-up · Type of knife · Stabbing velocity · Stabbing force

Availability of data
On reasonable request.

Introduction

Knives and sharp objects are among the oldest and most common weapons. Currently, there are no nationwide statistics on the number of knife attacks in Germany [14]. Stabbing injuries are of great importance in a forensic context. According to a German trauma register study, between 2009 and 2018, 4333 patients with a stabbing wound were registered, mostly associated with crimes of violence or suicide [2]. In legal proceedings, experts are often confronted with biomechanical aspects of stab wounds, for example concerning stabbing forces, kinematics of stabbing, etc. [13, 21]. According to [1], the expert opinion "given by forensic pathologists is often seen as 'critical' evidence in medico-legal situations." From a legal point of view, the assessment of the stabbing force is important as it allows conclusions to be drawn about the perpetrator's intension. Witness statements and

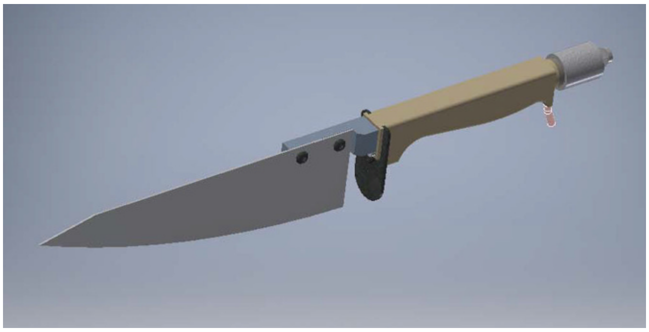

Fig. 1 ◀ Illustration of the measurement device

Fig. 2 ▲ Interchangeable blades

protective claims of the perpetrator should thus be assessed on a scientific basis. Parmar et al. [17] explained that in addition to the stabbing force, other variables make it difficult to assess what was happening, such as sharpness of the weapon, angle of attack or the relative movements of the opponents to one another. This illustrates the importance of forensic biomechanical basic research.

Overall, the number of studies addressing the biomechanics of stabbing is relatively small. Most of these studies do not contain systematic experimental measurements, for example using only one distinct blade etc. [11]. The current study focuses on the influence of blade shape on stabbing force.

The main objectives were:

- Development and calibration of an experimental set-up for quantification of dynamic stabbing kinematics and forces.
- Investigation of the influence of differently shaped blades on stabbing forces.

We hypothesize the lowest stabbing forces for the pointed blade, medium stabbing forces for the serrated blade and highest force values for the blunt blade. Furthermore, we assumed a significant influence of stabbing velocity on stabbing force, regardless of blade shape.

Material and methods

In cooperation with the medical device workshop (FSU Jena) a force measurement device was developed, which resembles the shape of a knife handle. The handle contains an integrated force sensor and a socket for mounting an accelerometer. Different blades can be fixed on the handle by two screws. In our tests we used blades of preferably different shapes in terms of a sharpened blade of a meat knife with a straight and pointed blade, a blade of a bread knife with a rounded tip and serrated cutting edge, both without handles. As a blunt knife we added an unsharpened straight back blunt blade workpiece. The tang, the part to fix the handle, was provided with drill holes, through which the blade can be screwed to the sensor unit. ◘ **Figures** 1 **and** 2 show a sketch of the experimental knife handle (◘ **Fig.** 1) and the selected three blades of different shapes (◘ **Fig.** 2). The length (L), the height (H) and the thickness (T) of the blades were as follows:

- Pointed blade: L = 9.5 cm, H = 1.5 cm, T = 0.1 cm (◘ **Fig.** 2, upper blade)
- Blunt blade: L = 10.5 cm, H = 2.0 cm, T = 0.3 cm (◘ **Fig.** 2, middle blade)
- Serrated blade: L = 11.5 cm, H = 1.7 cm, T = 0.1 cm (◘ **Fig.** 2, lower blade)

The sensor and data logger specifications were as follows: Disynet (Brüggen, Germany) force sensor XFTC-301–2 kN-/I5M (±2 kN), Disynet accelerometer DA 2502–500 (±500 g), Disynet µBOX-IEPE-5N/5S/5H Datalogger (sampling rate up to 50 kHz) with external custom-made amplifier (medical device workshop of the Jena University Hospital). The following software were used: QuickDAQ data logging software (MC measurement Corporation, Norton, USA), Origin data analysis software (OriginLab, Northampton, USA), IBM SPSS Statistic tool (IBM Statistics, New York, USA). A high-speed camera, Mikroton MotionBLITZ (Mikroton, Gilching, Germany) EoSens mini1 (sampling rate up to 100 kHz), was used for videography. The video sequences were processed by SIMI Motion 2D Software (Simi Reality Motion Systems GmbH, Munich, Germany). As tissue surrogate Gelatine A type 250 Bloom (Carl Roth GmbH + Co KG, Karlsruhe, Germany), 15% by mass was used dissolved in purified water and heated up to a temperature of 70 °C. We poured the gelatine into three 1L clear buckets. After cooling down, one bucket each was fixed in line of sight to the high-speed camera on a table. Experimental stabbing was performed by one volunteer (male, 1.80 m, 85 kg). The handle was held in the right hand with the blade projecting from the ulnar aspect of the hand. The volunteer was instructed to perform reproducible stabs in terms of movement and velocity, as far as possible. The stabbing motion was performed in a craniocaudal direction with elbow joint extension. The stabbing sequence was carried out with three stabs per blade in one bucket, with a total of 27 measurements (9 per bucket).

We used linear regression to check force-velocity dependencies and tests on equality of median values to show a potential influence of the blade shape on the stabbing force. Stabbing force is defined as the maximum force measured along the longitudinal axis of the blade during the stab.

Results

The force sensor was statically calibrated with five different masses from 2.0–9.455 kg, placed on a horizontal plate mounted on the experimental knife handle. Each mass was measured twice and the average was used for linear regression. We obtained the following linear equa-

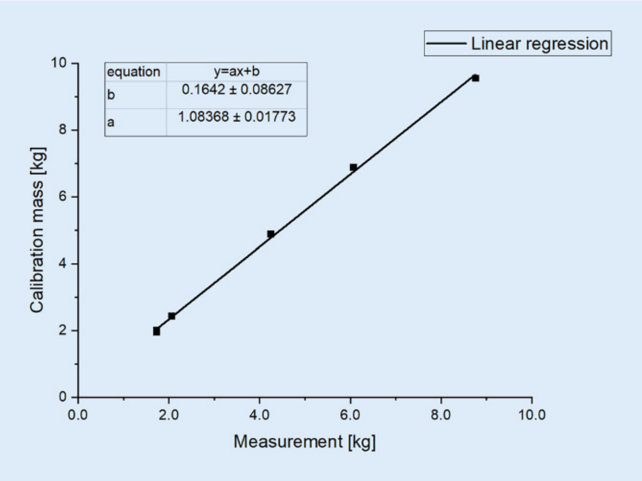

Fig. 3 ▲ Linear regression line, calibration of the force sensor

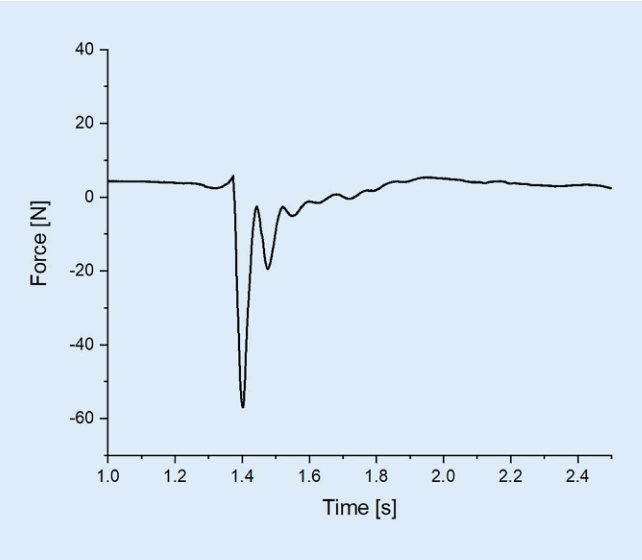

Fig. 4 ▲ Force curve of pointed blade (example)

tion: F (x) = 1.08368x + 0.1642, shown in ■ **Fig.** 3.

Time-force curves were analyzed in terms of maximum value using Origin (OriginLab). The time of maximum velocity coincides with the time point the tip of the blade first contacts the specimen.

■ **Figure** 4 shows one of the measurement curves as an example (pointed blade). The first deflection marks the point in time at which the tip of the knife hits the surface of the gelatine. The maximum stabbing force in this example is about 60 N. In the figure the force is negative due to the orientation of the sensor with negative compression and positive traction forces.

■ **Table** 1 summarizes the descriptive statistics of the maximum stabbing forces. In stabs with the blunt blade the highest forces with a mean of 107.3 N were obtained. Considerably lower maximum forces were obtained in stabs using the serrated and the pointed blades, while the mean maximum force for the serrated blade (72.6 N) is only slightly higher than for the pointed one (68.5 N). The mean maximum stabbing velocities ranged between 3.6 and 4.4 m/s. A dotplot with the maximum stabbing forces stratified by blade shape is illustrated in ■ **Fig.** 5.

Due to the small number of tests a normal distribution of the forces and velocities could not be assumed. Indeed, tests on normal distribution of the maximum forces stratified by knife type give *p*-values exceeding 0.05, so that formally a normal distribution could be assumed; however, looking at the histograms with a sample size of 9 each, we consider the assumption of normal distribution not reasonable. Therefore, a median test was carried out as a nonparametric statistical method. The results are shown in ■ **Table** 2. With a *p*-value, each of 0.001, significant differences of stabbing forces could be confirmed between the blunt blade and the pointed blade, and with the serrated blade. ■ **Figure** 6 shows the boxplot with the median values and the interquartile ranges.

A significant correlation between stabbing velocity and the stabbing force could only be demonstrated for the serrated blade. ■ **Figure** 7 shows the graphical depiction of the resulting regression line. The *p*-value is 0.033 with a R^2 value of 0.501 (■ **Table** 3). In contrast, there was no significant dependency between maximum velocity and maximum force for the pointed and blunt blade.

Discussion

Our set-up allows the simultaneous quantification of kinematic (velocity) and dynamic variables in terms of stabbing force and acceleration. The set-ups described in the literature mainly focused on force measurement [11, 15, 16] or kinematics [8]. Other studies [1, 7] included knives of different types but relatively similar in blade shape.

In our tests we used gelatine type A, 250 bloom as tissue surrogate. According to [9], "Hydrogels prepared from water solutions containing 10–20% gelatin are generally accepted muscle tissue surrogates in ballistic research". The advantages are the simple, standardized and inexpensive manufacturability. The use of the transparent gelatin in our also transparent 1 L buckets allowed furthermore conclusions about the penetration depth as well as the contour and angle of the puncture channel. This could be further investigated in future experiments by comparing those factors with the measured stabbing forces and shapes of the puncturing objects. In addition, morphological aspects obtained in experiments can also be useful in the context of stabbing wound reconstruction, using postmortem CT imaging [18]. It is worth mentioning that ballistic gelatine is not the material of choice for the reconstruction of blunt injuries [20]. In contrast to ballistic or stabbing incidents, blunt forces are associated with much lower contact pressures and energy densities.

We used gelatine type A, which is obtained from pigskin in an acidic process. Pigskin and cowhides have also been used as a skin substitute in science. According to [19], the simplified mechanical properties of gelatine (or polydimethylsiloxane) and the widely different mechanical properties

Table 1 Descriptive statistics of the maximum stabbing forces and maximum stabbing velocities stratified by knife type with mean, standard deviation, minimum and maximum values

Variable	Knife type	Mean	Standard deviation	Minimum	Maximum
Maximum force [N]	Pointed	68.5	9.5	57.0	83.6
	Serrated	72.6	10.8	54.8	85.8
	Blunt	107.3	17.2	78.7	129.3
Maximum velocity [m/s]	Pointed	3.9	0.33	3.5	4.4
	Serrated	3.6	0.5	2.7	4.3
	Blunt	4.4	0.4	4.0	5.0

Table 2 Median test: Stabbing forces depending on blade shape

Knife 1 vs. knife 2	Test statistics	*p*
Pointed vs. serrated	0.222	0.637
Pointed vs. blunt	***10.889***	***0.001***
Serrated vs. blunt	***10.889***	***0.001***

Values in italics if *p*-values less than 0.05

Table 3 Linear regression models: Influence of stabbing velocity on stabbing force with *p*-values and R^2-values

Knife type	*p*	R^2
Pointed	0.601	0.041
Serrated	***0.033***	***0.501***
Blunt	0.723	0.019

Values in italics if *p*-values less than 0.05

of animal skin are disadvantageous compared to artificial silicone-based polymeric material. In this respect, the use of artificial skin surrogates for further tests should be considered. As the focus of our tests was on the development of the basic measurement set-up and the comparison of the stabbing forces in dependency of blade shape, these disadvantages of gelatine as tissue surrogate appeared irrelevant.

The instrumentation of the handle with an accelerator sensor provides the opportunity to distinguish graphically the different phases of stabbing, e.g., the first contact between the tip of the knife on the surface or potential contact with other structures like the bottom of the specimen. The stabbing forces we measured averaged between 68.5 and 107.3 N (min. 54.8 N, max. 129.3 N). According to Knight [11], a sharp knife can penetrate skin with a weight-equivalent force of half a kilogram. Values between 30–50 N are given by the same research group for a blunt blade to penetrate cadaveric tissue. Skin and muscle present the highest resistance when penetrating human soft tissues. O'Callaghan et al. [16] stated that penetrating skin, muscle and fat requires a maximum stabbing force of 95.5 N. There are also older studies that report stabbing forces in the same order of magnitude [5, 6, 10]. For example, Fazekas et al. [5] found stabbing forces of 7.8 ± 4.58 kp in static tests. Similar stabbing forces were dynamically measured by Weber et al. [22].

Considering these forces, the values determined in the current study seem to be adequate to cause penetrating injuries using animal of human specimens. Significantly higher stabbing forces up to 2000 N were obtained by [4] and [3] when stabbing through stab-resistant material or ribs.

Parmar et al. [17] quantified the stabbing forces required for stabbing with blunt objects, such as screwdrivers with different heads, pens and chisels. As a result, the small-headed screwdrivers resembled the forces for sharp knifes, whereas those with bigger heads (> 2 mm^2) required forces for penetration of 70–130 N. These values appear comparable to those we measured for the blunt blade workpiece (78.7–129.3 N).

The blunt blade showed statistically significant higher stabbing forces compared to the pointed or the serrated blade. For the serrated blade, only a tendency towards higher resulting stabbing forces compared to the pointed one could be derived. In accordance with our results, Gilchrist [7] came to the conclusion that stabbing forces can differ with different blade shapes; however, if the construction conditions are not controlled, the piercing forces can differ by up to 100% with the same blade shape. An influence of the blade shape was also found in Fazekas et al. [6].

In addition to the properties of the knife, e.g., in terms of the shape of the impacting object, the severity of the resulting injury depends on the inflicted body part, the clothing [15], the effective mass and velocity.

In our tests, stabbing velocities ranged between 3.6 and 4.4 m/s. Miller and Jones [12] published a preliminary study in which the kinematics of four methods of stabbings were described. In the conclusions, overarm and underarm patterns are described as the two general but fundamental separate kinematic strategies of stabbings. A subdivision was made into short distance (short over-/short under-arm movement; behind a line 0.5 m from the target) and long distance (long over-/long under-arm movement, behind a line 1.25 m from the target) distances to the target. Our test set-up is most comparable to the short over variant. As a result, Miller's working group came up with an entry speed (short over) of the blade of 8.5 m/s with a standard deviation of 1.72 m/s. Horsefall et al. [8] let some volunteers stab twice in overarm action. While Miller's subjects were instructed to stab as hard and fast as possible, the volunteers of Horsefall et al. did not get such instructions. The mean terminal velocity of the knife was 8.5 m/s, which corresponds well to the results of Miller and Jones. We indeed attempted to execute the stabs with relative consistency and reproducibility at medium stabbing intensity, which explains our lower stabbing speeds.

Annaidh et al. [1] concluded, "that test speed has a significant effect on the penetration force ($p = 0.002$)." A statistically significant relationship between stabbing force and velocity in our tests was only proven for the serrated blade. That blade has a rounded tip and exhibits a more elastic deflection than the other ones often leading to a deviation from the vertical piercing axis. This could be a reason for the force-velocity dependency. Our results suggest that a dependency of the stabbing force on stabbing velocity in turn depends on knife properties. The fact that we could not statistically prove a difference in the median values of the stabbing

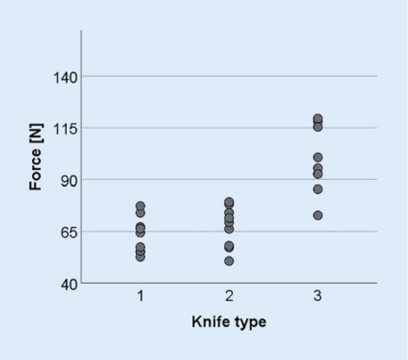

Fig. 5 ▲ Dotplot of stabbing forces for different knife types in terms of blade shape (*1*: pointed, *2*: serrated, *3*: blunt)

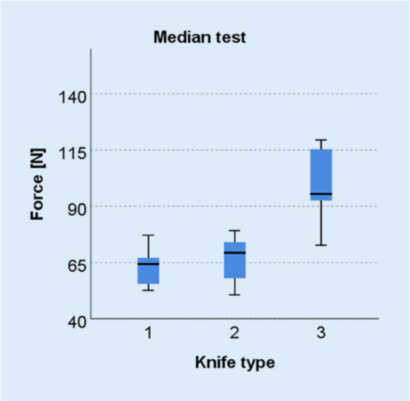

Fig. 6 ▲ Boxplot of maximum stabbing forces for different knife types in terms of blade shape (*1*: pointed, *2*: serrated, *3*: blunt)

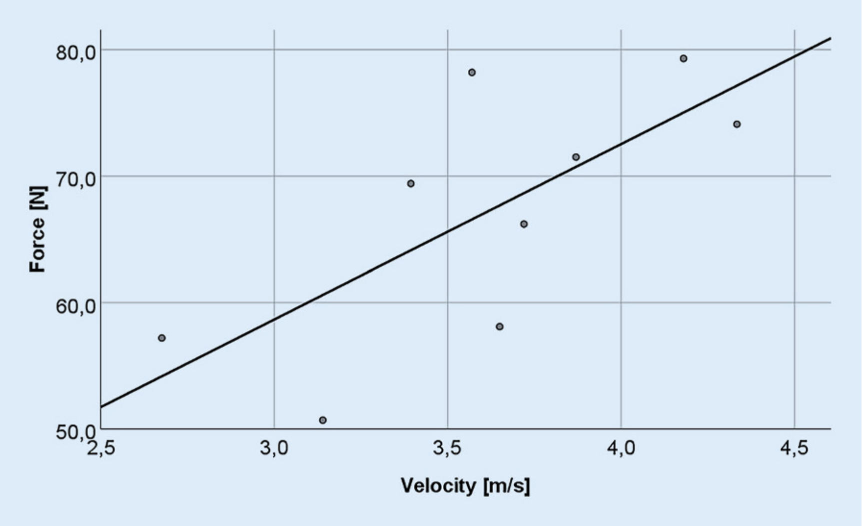

Fig. 7 ▲ Linear regression model: Stabbing velocity vs. stabbing force

forces comparing the pointed and serrated blade (◘ **Table 2**) might be ascribed to the force-velocity dependency only seen for the serrated one (◘ **Table 3**).

The stabbing velocity and in turn the stabbing force could be further influenced, e.g., by the shape of the handle, by different hand positions and by the stabbing movement. Especially, oblique impingement angles might bring about higher stabbing forces. The aforementioned factors are worth further investigation. Regarding the injury severity, an additional blunt force has to be considered when the most distal part of the handle impacts the target, which was not the case in our tests.

Several limitations concerning our set-up and measurements have to be taken into account. First, only one volunteer participated in order to blank out interindividual influences in the analysis of our results. Second, the stabbing speed and the effective mass were not controlled in the current study. This limitation can be addressed by using an appropriate set-up, such as a drop tower. Third, the number of 27 measurements with only 3 different blades seems to be too small for comprehensive statistical analysis. Fourth, stabbing velocities were captured within a 2-dimensional plane using only one high-speed camera. More exact velocity values could have been achieved using a three-dimensional motion analysis system; however, stabbing kinematics was performed in a plane perpendicular to the camera view, so that the authors do not expect relevant different results. Stabbing forces in tests using gelatine samples may not be exactly comparable to those using biomaterials. Up to now, first tests using pig cadavers were carried out and will be an issue of further experiments. Tests on human cadavers are desirable and are being planned, although hampered by ethical and practical obstacles.

Our results showed that general estimates concerning stabbing forces without considering case-specific circumstances can be fraught with substantial uncertainties. Reliable case evaluation needs the consideration of case-specific knives and circumstances. The set-up developed can be used in real casework as well as for the investigation of a wide spectrum of general biomechanical aspects of stabbing.

Conclusion

- Blade shape and stabbing velocity are factors influencing the resultant stabbing force.
- Reliable case evaluation needs the consideration of case-specific knives and circumstances.

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Declarations

Conflict of interest. T. Hunold, R. Spieß, D.K. Wissenbach, M. Hubig, G. Mall and H. Muggenthaler declare that they have no competing interests.

For this article no studies with human participants or animals were performed by any of the authors. All studies mentioned were in accordance with the ethical standards indicated in each case.

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Zusammenfassung

Abhängigkeit der Stichkraft von der Klingenform – Entwicklung eines experimentellen Setups und erste Ergebnisse

Hintergrund: In Gerichtsverfahren sollen Sachverständige häufig Stichkräfte abschätzen, welche für ein bestimmtes Verletzungsmuster erforderlich waren. Zu diesem Thema existieren nur wenige Studien.
Ziele: Entwicklung und Kalibrierung eines Versuchsaufbaus zur Quantifizierung dynamischer Stichbewegungen und -kräfte
Untersuchung des Einflusses unterschiedlich geformter Klingen auf die Stichkraft
Material und Methoden: Im Rahmen dieser Arbeit wurde ein Griff mit integriertem Kraft- und Beschleunigungssensor entwickelt und kalibriert. Verschiedene Klingen können am Griff befestigt werden. Es wurden 27 Messerstiche mit drei verschiedenen Klingen von einem Probanden durchgeführt. Als Gewebesurrogat diente Gelatine. Die Stichgeschwindigkeiten wurden mit einer Hochgeschwindigkeitskamera erfasst.
Ergebnis und Diskussion: Die Kalibrierung des Kraftsensors ergab eine nahezu perfekte lineare Regression. Die Stichgeschwindigkeiten lagen zwischen 2,7 und 5,0 m/s bei Stichkräften zwischen 54,8 und 129,3 N. Das Stechen mit der stumpfen Klinge resultierte in deutlich höheren Stichkräften im Vergleich zur spitzen oder gezahnten Klinge. Diese Tendenz zeigte sich auch für die gezahnte gegenüber der spitzen Klinge, jedoch ohne statistische Signifikanz. Eine signifikante Abhängigkeit der Stichgeschwindigkeit von der Stichkraft konnte nur für die gezahnte Klinge nachgewiesen werden.
Schlussfolgerung: Die Ergebnisse zeigen, dass sowohl die Stichgeschwindigkeit als auch die Klingenform die Stichkraft beeinflussen können. Für eine belastbare Begutachtung bedarf es daher einer Berücksichtigung des jeweiligen Tatmessers und der konkreten Fallumstände.

Schlüsselwörter
Messerstich · Stichversuche · Messertyp · Stichgeschwindigkeit · Stichkraft