

# Testing mechanical chest compression devices for pre-hospital patient transport under resuscitation

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## Research article

**Keywords:** cardio-pulmonary resuscitation, mechanical chest compressions, pre-hospital emergency medical services, transport, device stability

**Posted Date:** November 24th, 2020

**DOI:** <https://doi.org/10.21203/rs.3.rs-112953/v1>

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**Version of Record:** A version of this preprint was published on February 4th, 2021. See the published version at <https://doi.org/10.1186/s12873-021-00409-3>.

# Abstract

**1 Background** Mechanical chest compression (mCPR) offers advantages during transport under cardiopulmonary resuscitation. Little is known how devices perform en-route. Aim of the study was to measure performance of mCPR devices of different design during pre-hospital transport.

**2 Methods** We tested animax mono (AM), autopulse (AP), corpuls cpr (CC) and LUCAS2 (L2). The route had 6 stages (transport on soft stretcher or gurney involving a stairwell, trips with turntable ladder, rescue basket and ambulance including loading/unloading). Stationary mCPR with the respective device served as control. A four-person team carried an intubated and bag-ventilated mannequin under mCPR to assess device-stability (displacement, pressure point correctness), compliance with 2015 ERC guideline criteria for high-quality chest compressions (frequency, proportion of recommended pressure depth and compression-ventilation ratio) and user satisfaction (by standardized questionnaire).

**3 Results** All devices performed comparable to stationary use. Displacement rates ranged from 83% (AM) to 11% (L2). Two incorrect pressure points occurred over 15,962 compressions (0.013%). Guideline-compliant pressure depth was >90% in all devices and compression-ventilation ratio was 40% (AM), 87% (CC, L2 respectively) and 93% (AP). Electrically powered devices showed constant frequencies while muscle-powered AM showed more variability (median 100/min, interquartile range 9). Although physical effort of AM use was comparable (median 4.0 vs. 4.5 on visual scale), participants preferred electrical devices.

**4 Conclusion** All devices showed good to very good performance although device-stability, guideline compliance and user satisfaction varied by design. Our results underline the importance to check stability and connection to patient under transport.

## 1 Background

The use of mechanical chest compression (mCPR) devices does not provide an improved survival rate compared to manual chest compression [1–4]. However, there are situations in which mCPR appears to offer advantages and the guidelines of the European Resuscitation Council (ERC) consider mCPR devices as a "reasonable alternative" [5, 7, 8]. This may especially be true in situation when patient transport under ongoing cardiopulmonary resuscitation becomes necessary in order to perform interventions at the hospital, e.g. catheter intervention. However, protracted manual chest compression leads to a loss of quality during resuscitation and is negatively influenced under transport conditions [9–12].

The aim of this study was to evaluate mechanical chest compression devices in pre-hospital patient transport under resuscitation regarding potential design differences under realistic conditions of use.

## 2 Methods

### 2.1 mCPR devices

Four devices were tested: animax mono (AAT Alber Antriebstechnik GmbH, Albstadt, Germany), AutoPulse reanimation system model 100 (ZOLL Medical Corporation, Chelmsford, Massachusetts, USA), corpuls cpr (GS Elektromedizinische Geräte G. Stemple GmbH, Kaufering, Germany) and LUCAS2 (Physio-Control, Inc., Redmond, Washington, USA). Animax mono is operated by muscle power. The other devices have an autonomous electric drive system. Animax mono, corpuls cpr and LUCAS2 have a stamp mechanism; AutoPulse employs a load distributing band (LDB) that compresses the thorax semi-circularly. The devices have been described in detail elsewhere [13, 14].

## 2.2 Transport team

Nine paramedics and four emergency physicians participated in this study, building a four-person transport team to carry a mannequin under mCPR along a pre-defined route. The turntable ladder was operated by a crew from Munich Fire Department.

## 2.3 Mannequin and equipment

The intubated mannequin (Ambu® Man W (Wireless); Ambu GmbH (Bad Nauheim, Germany)) weighed 14 kg. We added 50 kg of lead pellets to increase the load. In addition, the team had to carry a defibrillator (LIFEPAK® 15; Physio-Control, Inc., Redmond, Washington, USA) and a 2-litres oxygen cylinder with pressure reducer. Transport teams were trained in proper use of the mCPR devices and worked under supervision by manufacturer representatives.

## 2.4 Route and procedure

The 10 stages of the route consisted of transport with a *soft stretcher* or *gurney involving* a stairwell, vehicular trips with *turntable ladder* and rescue basket and *ambulance transport*, as well as *loading* and *unloading*.

During transport, a member of the transport team ventilated the mannequin using a respiratory bag in a compression-ventilation ratio of 30:2 (exceptions: *ambulance transport*. continuous use of mCPR device and mechanical ventilation with MEDUMAT Standard (WEINMANN Emergency Medical Technology GmbH, Hamburg, Germany); *rescue basket* - ventilation with an Oxylator (CPR Medical Devices, Inc., Markham, Ontario, Canada)).

## 2.5 Data collection

Resuscitation data was recorded using Ambu CPR Software (Version 3.1.1). Data were collected for each stage individually. Transport teams were blinded to the recordings.

## 2.6 Endpoints

The study endpoints included stability of the device and compliance with guideline criteria for high-quality cardiac massage according to 2015 ERC guidelines.

For this purpose, compliance with the correct pressure point was analysed; for chest compression this point was on the lower half of the sternum for all mCPR devices with exception of AutoPulse [15]. Deviations in the mCPR devices' connection position were measured in cranio-caudal or lateral direction

using callipers and a scale burned into the skin of the mannequin. For AutoPulse, lateral displacement was defined as twisting of the LDB in the frontal plane. If dislocation occurred, devices were re-adjusted at the end of each stage. In addition, the number of stages with correction of the connection position was compared to those without.

Criteria for high-quality chest compression included compliance with a compression depth of 50–60 mm and a compression-ventilation ratio of 30:2. Rounded means of complete compression-ventilation cycles with "30:2" were classified as "OK" and "Not OK" if this was not the case.

The guideline recommended frequency of 100–120 chest compressions per minute can be guaranteed only by *corpuls cpr* and *LUCAS2*. *Autopulse* is set by the manufacturer to a frequency of 80 per minute; *animax mono* is user-dependant.

The transport team evaluated each mCPR device after each run on a standardized questionnaire using visual analogue scale from 0 ("totally unsuitable") to 10 ("ideally suited") in four categories and ranked the perceived physical effort using a modified BORG CR-10 scale (0  $\triangleq$  no exertion/breathlessness; 10  $\triangleq$  maximum exertion/breathlessness forces stop) [16]. Additionally, positive or negative aspects could be indicated in open text responses.

## 2.7 Study design

The test sequence of the devices was carried out following a web-based block randomization (<https://www.randomizer.org/>; G. C. Urbaniak and S. Plous; last visited on: 10/09/2014). Two passes were completed (second pass modified: no trip with *rescue basket*, one instead of two *turntable ladder* transports).

For statistical analysis, similar action sequences, such as basic resuscitation, loading and unloading of the ambulance, or all turntable ladder movements were grouped accordingly resulting in 6 groups that underwent statistical analysis. Stationary mCPR (*basic resuscitation*) at the beginning and end of the transport served as control group.

Data were checked for normal distribution using Shapiro-Wilk test. Numerical data is given as median with interquartile range (IQR) and categorical data as percentage (%). Unless otherwise specified, we used Fisher's exact test for comparison of categorical data due to small sample size. Statistical tests were selected according to type of feature and type of scale level:  $p < 0.05$  was considered a statistically significant difference.

The study protocol was reviewed and approved by the Ethics Committee at the Medical Faculty of the LMU Munich (EK Nr. 493 – 15). Members of the transport team gave consent to participate in the study.

# 3 Results

## 3.1.1 Device-stability under transport conditions

### 3.1.1.1 Correct pressure point

An incorrect pressure point was recorded for 2 of 15,962 compressions (0.013%). Both were measured at the beginning of the application of corpuls cpr during soft stretcher transport.

### 3.1.1.2 Pressure Point Displacement

Table 1  
gives an overview of maximum displacements in cranio-caudal and lateral directions.

Device	Max. displacement (cm)	
	cranio-caudal	lateral
animax mono	4.5	1.0
AutoPulse	2.3	2.2
corpuls cpr	1.7	1.0
LUCAS 2	0.5	0.4

Table 1: *Devices and their maximum displacements (cranio-caudal; lateral)*

Comparing connection-point-dislocation, animax mono is particularly striking. During transport with the *gurney*, the pressure point shifted by up to 4.5 cm, while no shifting was observed with all other devices during this stage. The connection points for AutoPulse and corpuls cpr shifted up to 2.3 cm and 1.7 cm, respectively. Cranio-caudal slippage of LUCAS2 occurred only during *basic resuscitation* and ambulance transport and was significantly lower, with a maximum of 0.5 cm.

In the lateral direction, animax mono and corpuls cpr showed stamp-deviations of up to 1.0 cm, while LUCAS2 slipped less (max. 0.4 cm). AutoPulse's LDB twisted through the frontal plane by up to 2.2 cm.

None of the detected displacements led to detection of an incorrect pressure point.

### 3.1.1.3 Frequency of correction after slipping

The total number of corrections after slippage was used to compare device-stability.

Table 2  
Comparison of corrections after each route stage (by device)

Device		Correction of pressure point required?	
		No	Yes
<b>animax mono</b>	Number of subsections observed	3	15
	Percent	17%	83%
	Expected number	9.5	8.5
<b>AutoPulse</b>	Number of subsections observed	10	8
	Percent	56%	44%
	Expected number	9.5	8.5
<b>corpuls cpr</b>	Number of subsections observed	9	9
	Percent	50%	50%
	Expected number	9.5	8.5
<b>LUCAS 2</b>	Number of subsections observed	16	2
	Percent	89%	11%
	Expected number	9.5	8.5

Pairwise comparison showed significant differences in the transport stability of AutoPulse ( $p = 0.04$ ) and LUCAS2 ( $p < 0.001$ ) compared to animax mono, In addition, the LUCAS2 had to be corrected significantly less often than the corpuls cpr ( $p = 0.03$ ).

### 3.1.2 Proportion of compressions meeting guideline pressure depth

The proportions of compressions with pressure depth meeting the guidelines under transport conditions were compared to *basic resuscitation* in stationary operation, separated by device and stage (Fig. 1).

Overall, compression performance for all devices was over 90% on most stages. One outlier was observed with animax mono during *rescue basket* transport, where only 59.0% of the compressions had recommended depth (40.1% were too deep). On the remaining stages, 91.5% of compressions had a depth meeting guidelines (Fig. 1).

With AutoPulse applied during *soft stretcher* transport, compression performance could be assessed only to a limited extent (49.6%) compared to other stages, because a data cable disconnected during the first run and interrupted recording (\* in Fig. 1)

Over all stages, LUCAS2 achieved the most consistent and best results: for *basic resuscitation* it achieved the lowest value of 94.7% (median 98.8%, IQR: 4.30) but performed comparably well as in the *ambulance*

loading procedure (98.2%, IQR 2.93).

One conspicuous result was that with all electrically powered mCPR devices (AutoPulse, corpuls cpr and LUCAS2) greater scattering in the guideline-compliant pressure depth was observed during *basic resuscitation*

### 3.1.3 Frequency stability

As shown in Fig. 2, frequency for LUCAS2 (102/min), corpuls cpr (100/min) and AutoPulse (80/min) was consistently achieved (IQR 0). The deviation (\* in Fig. 2) during *soft stretcher* transport was mentioned above. Compression rate for the muscle-powered animax mono showed greater variability (100/min, IQR: 9).

### 3.2.2 Compression-ventilation ratio

The devices were tested pair-wise for significant differences in the compression-ventilation ratio.

Table 3  
Comparison of the 30:2 compression-ventilation ratio by route (for each device)

Device		"30:2" ratio	
		Not OK	OK
animax mono	Number of subsections observed	9	6
	Percentage	60.0%	40.0%
	Expected number	3.6	11.4
AutoPulse	Number of subsections observed*	1	13
	Percent	7.1%	92.9%
	Expected number	3.3	10.7
corpuls cpr	Number of subsections observed*	2	13
	Percentage	13.3%	86.7%
	Expected number	3.6	11.4
LUCAS 2	Number of subsections observed	2	13
	Percentage	13.3%	86.7%
	Expected number	3.6	11.4

In the first run, data recording was interrupted during soft stretcher transport with AutoPulse (\* in Table 3). As a result, *n* was reduced here from 15 to 14. Animax mono differed significantly from AutoPulse ( $p =$

0.005), corpuls cpr (p = 0.02) and LUCAS2 (p = 0.02). The other devices performed similarly in the comparisons (data not shown).

### 3.2.3 Assessment by the users

Study participants evaluated the devices in four categories (1  $\triangleq$  totally unsuitable; 10  $\triangleq$  ideally suited). Physical burden was assessed on the modified BORG scale.

Table 4  
Subjective satisfaction and physical burden (BORG scale) when using the various mCPR devices; p-values from the Kruskal-Wallis tests for each category

	Satisfaction when carrying  (without turntable ladder operator)	Satisfaction when loading/unloading ambulance  (without turntable ladder operator)	Satisfaction when using the turntable ladder  (all)	Overall satisfaction  (without turntable ladder operator)	Physical burden  (BORG scale; without turntable ladder operator)
animax mono	3.5 (IQR 4)	5.0 (IQR 4)	4.0 (IQR 8)	5.0 (IQR 5)	4.5 (IQR 3)
AutoPulse	9.0 (IQR 2)	9.0 (IQR 2)	10.0 (IQR 2)	9.0 (IQR 1)	4.0 (IQR 3)
corpuls cpr	9.5 (IQR 2)	9.0 (IQR 1)	9.0 (IQR 2)	9.0 (IQR 1)	4.0 (IQR 3)
LUCAS 2	9.0 (IQR 3)	10.0 (IQR 2)	10.0 (IQR 1)	9.5 (IQR 2)	4.0 (IQR 2)
p-value	0.001	0.002	0.010	0.001	0.754

Use of the electrically powered mCPR devices showed a high level of satisfaction, regardless of the category. The manually operated animax mono achieved worse values, although effort during transport was rated almost equally on the modified BORG scale

With medians of 4.0 (AutoPulse, corpuls cpr IQR 3; LUCAS2 IQR 2) and 4.5 (animax mono IQR 3), respectively, perceived physical burden corresponded to a (marked) exertion, which *by definition* was accompanied by noticeable but controllable breathing. Analysis of satisfaction showed clear differences in the Kruskal-Wallis test: In the pair-wise comparison using the Mann-Whitney U test, the animax mono showed a significantly poorer performance *post hoc* compared to the other three mCPR devices (Table 4).

## 4 Discussion

In our study, the mCRP devices examined all yielded good results with respect to effective chest compression during pre-hospital patient transport. Design-related differences in stability were found, but did not lead to any clinically relevant worsening of chest compression parameters.

Transport situations using mCPR devices that have been investigated to date primarily include ambulance, turntable ladders and helicopter transport [17–20]. In the study by Lyon et al., use of a *soft stretcher* with AutoPulse achieved good results and was presented as a possibility for improved rescue measures [21].

Sunde et al. examined compression quality at the site of the incident, when walking on a horizontal plane and on stairs [22]. On the basis of these data and on the study of Gaessler et al., observing lower quality in manual chest compression during ambulance and braking manoeuvres, the use of mCPR devices represents a possibility for effective chest compression with protracted resuscitation [23].

Over the course of the entire test, only once did two false pressure points occur (corpuls cpr: at beginning of *soft stretcher* transport). However, since the connection point immediately before the two compressions registered as "incorrect" was checked and found to be correct for the subsequent stages, the most likely reason for an incorrect measurement was that the number of incorrect pressure points of the mCPR devices was low or equal to 0, as in other studies [17, 19, 24].

Nevertheless, displacement of the connection point to the patient was most pronounced with animax mono. Shear and tensile forces on the control lever, which can be turned in all directions, are felt to be the cause, as they promote slippage at the connection point; in contrast to the results of Gaessler et al., in our study this did not lead to an incorrect pressure point [17, 24]. The electrically powered mCPR devices seemed to be less susceptible to external forces by using a LDB (AutoPulse), spineboard (corpuls cpr) or stabilisation belts (LUCAS2).

During the tests, care was always taken to ensure that the mannequin was correctly secured on the gurney, but the manufacturer's precautions (e.g. operate the device only when it is in a secure position) during transport were deliberately disregarded in order not to unnecessarily complicate analysis of the basic data and to reflect realistic use [25, 26]. Despite more or less marked instability, the devices had only a very low risk of slipping in such a way that the correct pressure point would have been lost, from which it can be deduced that regular checks of the compression point are necessary when using mCPR under transport. If this is ensured, as in our experimental design, and any deviations are corrected promptly, then correct cardiac massage should be possible with all devices tested even under transport conditions.

With the manually operated animax mono, the percentage of compressions that were too deep when used in the *rescue basket* stage (40.1%) was noticeably high. Because there was no high-altitude rescuer available to operate the device, we recorded fewer compressions in absolute terms than in electrically powered mCPR devices, but mechanical resistance in the device should actually prevent compressions that are too deep. One explanation for this observation could be, as with displacements, shear forces at

the compression point. In the case of electrically powered mCPR devices, adjustments to the devices via automated calibrations may have played a role with respect to better values during transport: If the compressing agents were paused between stages in order to check the compression point, this could have led to better adaptation to the mannequin. In contrast to the study by Fox et al., the study by Gaessler et al. on ambulance transport with LUCAS2 did not show any compression with a pressure depth that was in line with guidelines [19, 24]. This is an indication that the simulator results for the "proportion of compressions with pressure depth that meets guidelines" must be considered with caution. The mannequin selected by Gaessler et al. [17, 24] could only inadequately represent the dimensions of a human thorax, whereas the mannequin used in our tests seems to be more suitable. According to the manufacturer, corpuls cpr adjusts to the elasticity of the thorax. Use on a mannequin might have led to incorrect pressure depth and thus cannot be transferred to humans. This may also explain the greater scattering in pressure depth observed during *basic resuscitation*.

Animax mono was subject to fluctuations in frequency and compression-ventilation ratio compared to electrically powered mCPR devices. These were most likely due to the manual operation and related transport influences. More than half of all stages were classified as "Not OK" with respect to the "30:2" compression-ventilation ratio. Measurement of compression frequency revealed that animax mono ranged from 88 to 112 compressions/minute; however, with a median of 100/min (IQR 9), this value was within the recommended range of 100–120/min) [15]. Gaessler et al. made similar observations [17, 24]. However, operation of animax mono requires full attention of the operator, whereas with automated mCPR devices, user interactions such as pauses in ventilation are indicated by an acoustic and/or optical signal. Sunde et al. showed that this makes it easier to maintain the correct compression-ventilation ratio [22]. Consistent frequency of electrically powered mCPR devices has been confirmed in other studies [17, 19, 24].

In all "satisfaction" categories, medians were at least 9.0 for electrically powered devices. Animax mono received significantly lower values ranging from 3.5 ("satisfaction when carrying") to 5.0 ("satisfaction in loading/unloading the ambulance" or "overall satisfaction"). The similarly good performance of all devices for the category "physical burden" was surprising. Obviously, the control lever of animax mono minimized work so much that despite the long muscle-based operation, virtually no increased physical burden was perceived. Overall, participants rated the entire transport on the modified BORG scale as "somewhat/reasonably strenuous". In the study by Fox et al., however, rescuers rated just an eight-minute manual chest compression on the BORG scale (RPE scale; values: 6–20) as "somewhat strenuous" (mean 13.6) [19]; Animax mono's independence from a battery received not only praise but also disadvantages during transport. An assistant had to operate the device continuously; at the same time, operation of the lever was problematic when using the turntable ladder basket or the cot's transport frame. During these situations, the lever was elevated to a height that restricted the operator to completely release it to the resting position [27]. AutoPulse was praised for its "flat" design. However, study participants expressed criticism of the large back plate, which led to obstacles when laying the mannequin on the ambulance gurney. The chest compression strap also made it impossible to secure the mannequin correctly on the gurney. For corpuls cpr, participants evaluated the possible combination of a resuscitation arm with a

spineboard very differently: immobilization was praised, while the effort required was viewed negatively. LUCAS2 was praised for its simplicity.

A primary limitation of the study is that the mannequin chosen does not allow assessment of blood flow to brain and coronary vessels. Physiological parameters - for ventilation as well - for the assessment of compression quality using mCPR during transport could not be verified. Furthermore, it was shown that resuscitation mannequins could influence the results because their biomechanical properties do not adequately represent the human body and the built-in measuring devices do not have the desired precision, at least for some of the parameters recorded. This study was purely descriptive. However, the small number of cases limits the informative value of the results.

## 5 Conclusion

Along a transport route with typical obstacles such as stairs, turntable ladders or loading procedures and transport in an ambulance, all mCPR devices investigated in this study showed good to very good performance during transport under cardio-pulmonary resuscitation. Stability of the devices varied during transport, with no relevant incorrect pressure points observed. However, the results also show how important it is to regularly check stability and correct connection to the patient under transport conditions and to correct if necessary. However, when transferring the test to reality, losses in chest compression quality or injuries to the patient cannot be ruled out. Differences in the design of the devices were also reflected in the variable ratings by study participants. Interestingly, the use of animax mono, a purely muscle-powered device, did not mean higher physical burden. Automation seems to increase quality of resuscitation.

## 6 Abbreviations

ÄLRD	Ärztlicher Leiter Rettungsdienst
ca.	circa
cm	Zentimeter
CPR	cardiopulmonary resuscitation
ERC	European Resuscitation Council
et al.	et alii (and others)
GmbH	Gesellschaft mit beschränkter Haftung
Inc.	Incorporated
INM	Institut für Notfallmedizin und Medizinmanagement

IQR	interquartile range
LUCAS	Lund University Cardiac Assist System
LMU	Ludwig-Maximilians-Universität München
mCPR	mechanical cardiopulmonary resuscitation
p	page
%	percent

## 7 Declarations

### **Ethics approval and consent to participate**

The ethics committee (Ethikkommission bei der Medizinischen Fakultät der LMU München, Pettenkoferstr. 8a, 80336 München) approved the study (committee's reference number: 493-15)

### **Consent to publish**

If the manuscript contains any individual person's data, all persons involved agreed to publish the data.

### **Availability of data and materials**

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

### **Competing interests**

The authors declare that they have no competing interests

### **Funding**

The study did not receive any financial support from these participating companies.

### **Authors' contributions**

All authors have read and approved the manuscript. MJ was responsible for methodology, investigation, formal analysis, data curation, writing the original draft and visualization; JK and HH for term, conceptualization, investigation, review & editing. Both KK and TB worked on term, conceptualization, formal analysis, review & editing. SP was responsible for term, conceptualization, resources, review & editing and supervision; BZ for review & editing and supervision. HT was responsible for term, conceptualization, methodology, formal analysis, investigation, data curation, visualization, writing the original draft, supervision and project administration.

## Acknowledgements

This work is part of the doctoral thesis of Maximilian Jörgens (- not publish yet).

We would like to thank all members of Berufsfeuerwehr München, Feuerwache 6, Bassermannstraße 20, 81245 München who supported and participated in this study.

We also would like to thank the companies (AAT Alber Antriebstechnik GmbH, ZOLL Medical Corporation, GS Elektromedizinische Geräte G. Stemple GmbH and Physio-Control, Inc.) and their representatives for supporting this study by providing the mCPR devices and the instructions for their proper use.

## References

- [1] Perkins GD, Lall R, Quinn T, Deakin CD, Cooke MW, Horton J, et al. Mechanical versus manual chest compression for out-of-hospital cardiac arrest (PARAMEDIC): a pragmatic, cluster randomised controlled trial. *The Lancet*. 2014.
- [2] Smekal D, Johansson J, Huzevka T, Rubertsson S. A pilot study of mechanical chest compressions with the LUCAS device in cardiopulmonary resuscitation. *Resuscitation*. 2011;82:702-6.
- [3] Gates S, Quinn T, Deakin CD, Blair L, Couper K, Perkins GD. Mechanical chest compression for out of hospital cardiac arrest: Systematic review and meta-analysis. *Resuscitation*. 2015;94:91-7.
- [4] Ji C, Lall R, Quinn T, Kaye C, Haywood K, Horton J, et al. Post-admission outcomes of participants in the PARAMEDIC trial: A cluster randomised trial of mechanical or manual chest compressions. *Resuscitation*. 2017;118:82-8.
- [5] Soar J, Nolan JP, Böttiger BW, Perkins GD, Lott C, Carli P, et al. Erweiterte Reanimationsmaßnahmen für Erwachsene („adult advanced life support“): Kapitel 3 der Leitlinien zur Reanimation 2015 des European Resuscitation Council. 2015;18:770-832.
- [6] Arntz HR, Agrawal R, Richter H, Schmidt S, Rescheleit T, Menges M, et al. Phased chest and abdominal compression-decompression versus conventional cardiopulmonary resuscitation in out-of-hospital cardiac arrest. *Circulation*. 2001;104:768-72.
- [7] Bekgoz B, San I, Ergin M. Quality Comparison of the Manual Chest Compression and the Mechanical Chest Compression During Difficult Transport Conditions. *J Emerg Med*. 2020;58:432-8.
- [8] Magliocca A, Olivari D, De Giorgio D, Zani D, Manfredi M, Boccardo A, et al. LUCAS Versus Manual Chest Compression During Ambulance Transport: A Hemodynamic Study in a Porcine Model of Cardiac Arrest. *J Am Heart Assoc*. 2019;8:e011189.
- [9] Olasveengen TM, Wik L, Steen PA. Quality of cardiopulmonary resuscitation before and during transport in out-of-hospital cardiac arrest. *Resuscitation*. 2008;76:185-90.

- [10] Odegaard S, Olasveengen T, Steen PA, Kramer-Johansen J. The effect of transport on quality of cardiopulmonary resuscitation in out-of-hospital cardiac arrest. *Resuscitation*. 2009;80:843-8.
- [11] Sugerman NT, Edelson DP, Leary M, Weidman EK, Herzberg DL, Vanden Hoek TL, et al. Rescuer fatigue during actual in-hospital cardiopulmonary resuscitation with audiovisual feedback: a prospective multicenter study. *Resuscitation*. 2009;80:981-4.
- [12] Slattery DE, Silver A. The hazards of providing care in emergency vehicles: an opportunity for reform. *Prehospital emergency care : official journal of the National Association of EMS Physicians and the National Association of State EMS Directors*. 2009;13:388-97.
- [13] Fischer M, Breil M, Ihli M, Messelken M, Rauch S, Schewe JC. Mechanische Reanimationshilfen. *Der Anaesthesist*. 2014;63:186-97.
- [14] Luxen JP, Birkholz T, Hatz A, Kanz KG, Königer J, Meier M, et al. Nutzen mechanischer Reanimationshilfen bei der kardiopulmonalen Reanimation. *Notfall + Rettungsmedizin*. 2015;18:119-29.
- [15] Perkins GD, Handley AJ, Koster RW, Castrén M, Smyth MA, Olasveengen T, et al. Basismaßnahmen zur Wiederbelebung Erwachsener und Verwendung automatisierter externer Defibrillatoren: Kapitel 2 der Leitlinien zur Reanimation 2015 des European Resuscitation Council. *Notfall + Rettungsmedizin*. 2015;18:748-69.
- [16] Borg G. Anstrengungsempfinden und körperliche Aktivität. *Deutsches Ärzteblatt*. 2004;101:1016-21.
- [17] Gassler H, Kummerle S, Ventzke MM, Lampl L, Helm M. Mechanical chest compression: an alternative in helicopter emergency medical services? *Internal and emergency medicine*. 2015;10:715-20.
- [18] Putzer G, Braun P, Zimmermann A, Pedross F, Strapazzon G, Brugger H, et al. LUCAS compared to manual cardiopulmonary resuscitation is more effective during helicopter rescue-a prospective, randomized, cross-over manikin study. *The American journal of emergency medicine*. 2013;31:384-9.
- [19] Fox J, Fiechter R, Gerstl P, Url A, Wagner H, Luscher TF, et al. Mechanical versus manual chest compression CPR under ground ambulance transport conditions. *Acute cardiac care*. 2013;15:1-6.
- [20] Drinhaus H, Nusgen S, Adams N, Wetsch WA, Annecke T. Rescue under ongoing CPR from an upper floor: evaluation of three different evacuation routes and mechanical and manual chest compressions: a manikin trial. *Scandinavian journal of trauma, resuscitation and emergency medicine*. 2020;28:16.
- [21] Lyon RM, Crawford A, Crookston C, Short S, Clegg GR. The combined use of mechanical CPR and a carry sheet to maintain quality resuscitation in out-of-hospital cardiac arrest patients during extrication and transport. *Resuscitation*. 2015;93:102-6.
- [22] Sunde K, Wik L, Steen PA. Quality of mechanical, manual standard and active compression-decompression CPR on the arrest site and during transport in a manikin model. *Resuscitation*.

1997;34:235-42.

[23] Gaessler H, Ventzke MM, Lampl L, Helm M. Transport with ongoing resuscitation: a comparison between manual and mechanical compression. *Emergency medicine journal : EMJ*. 2013;30:589-92.

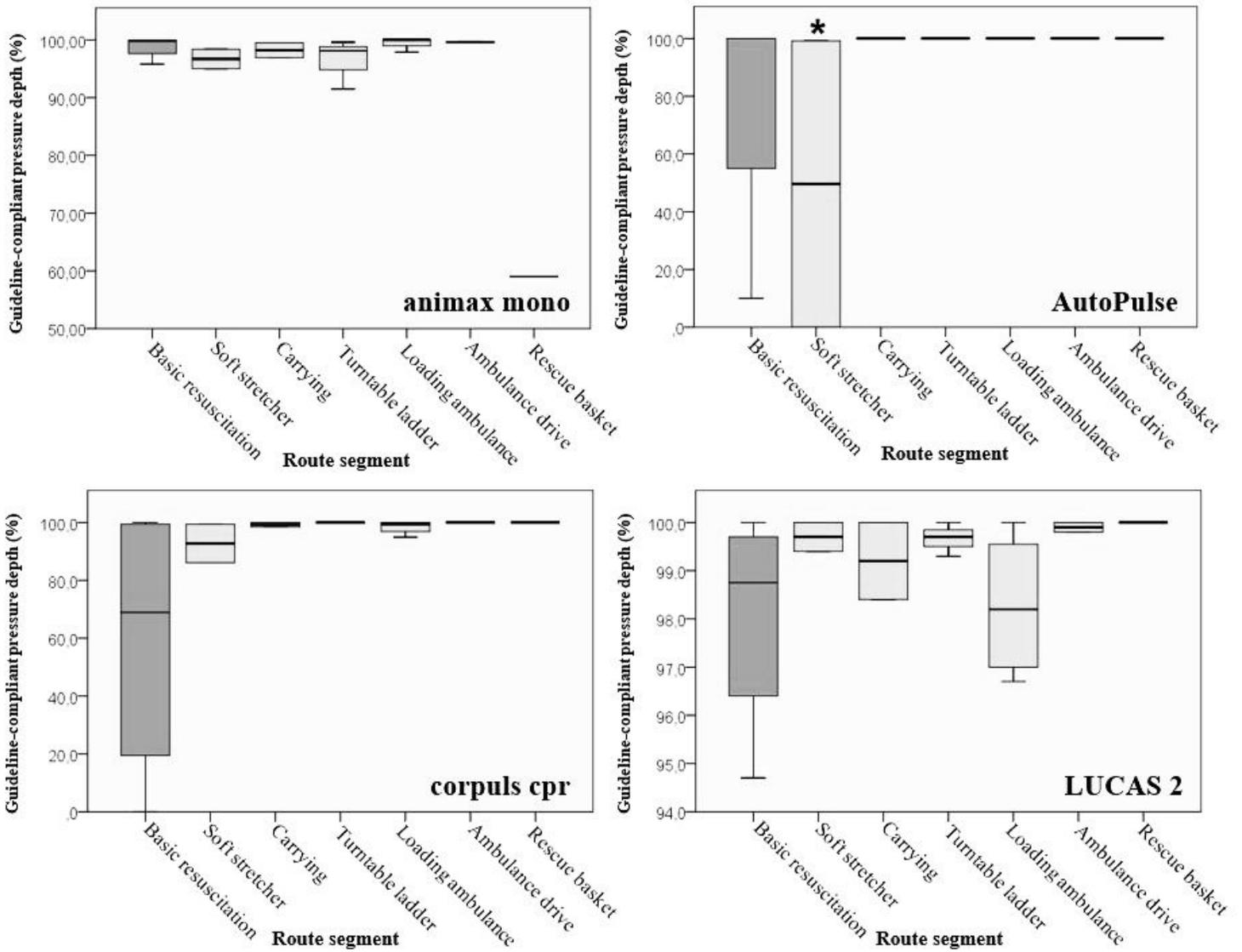
[24] Gassler H, Ventzke MM, Lampl L, Helm M. Transport with ongoing resuscitation: a comparison between manual and mechanical compression. *Emergency medicine journal : EMJ*. 2013;30:589-92.

[25] LUCAS™2 - Thoraxkompressions-System Bedienungsanleitung (Physio-Control). Jolife AB; 2011. p. 100666-02 B.

[26] AutoPulse® Reanimationssystem Modell 100 Bedienerhandbuch (Zoll Medical Corporation). ZOLL; 2012.

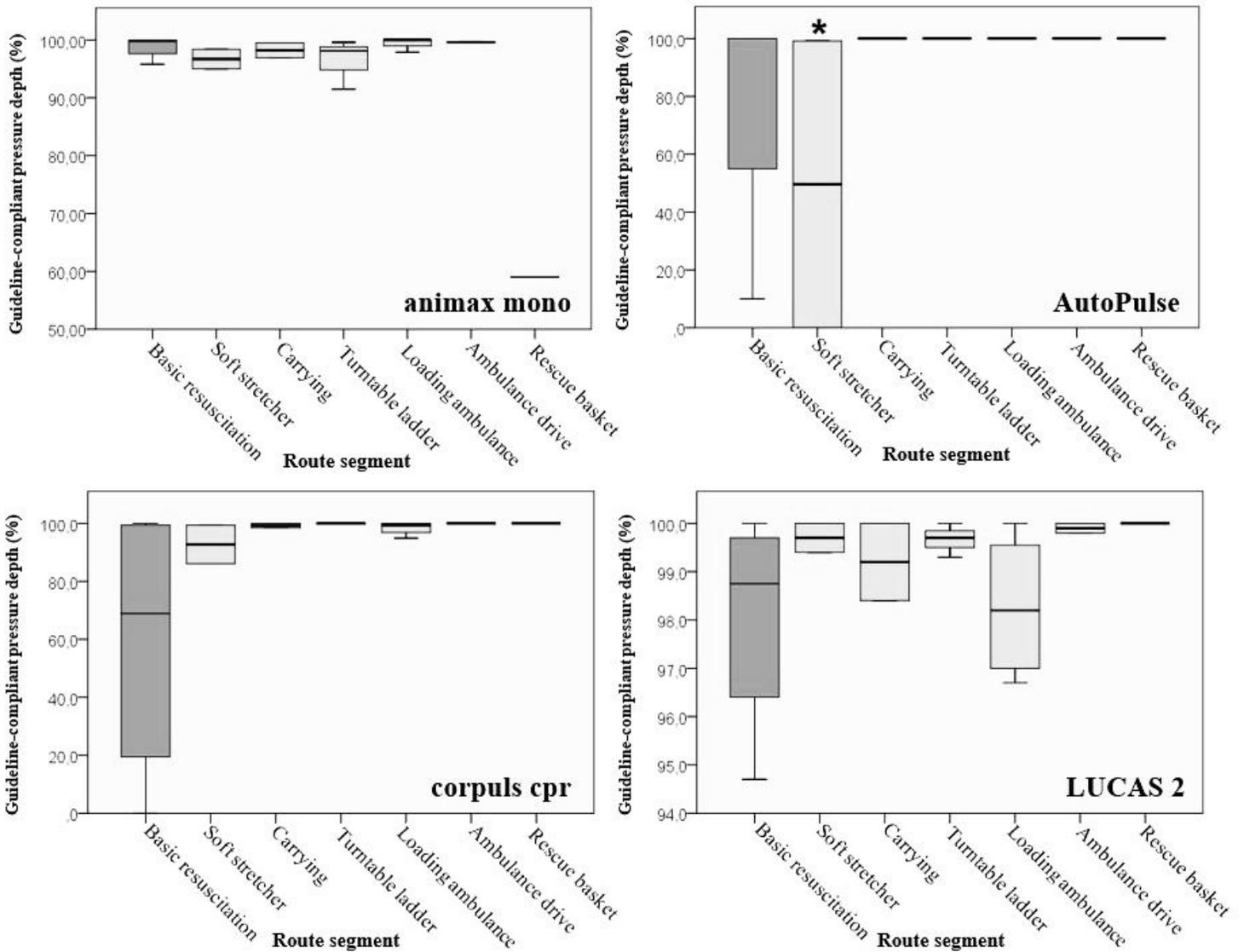
[27] animax-mono Bedienungsanleitung (AAT Alber Antriebstechnik GmbH). AAT Alber Antriebstechnik GmbH.

## Figures



**Figure 1**

Proportion of compression with pressure depth meeting guidelines (%), by device and route. (\*) Faulty data recording on the first run (- unintended termination after 20 seconds; limited information)



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Proportion of compression with pressure depth meeting guidelines (%), by device and route. (\*) Faulty data recording on the first run (- unintended termination after 20 seconds; limited information)

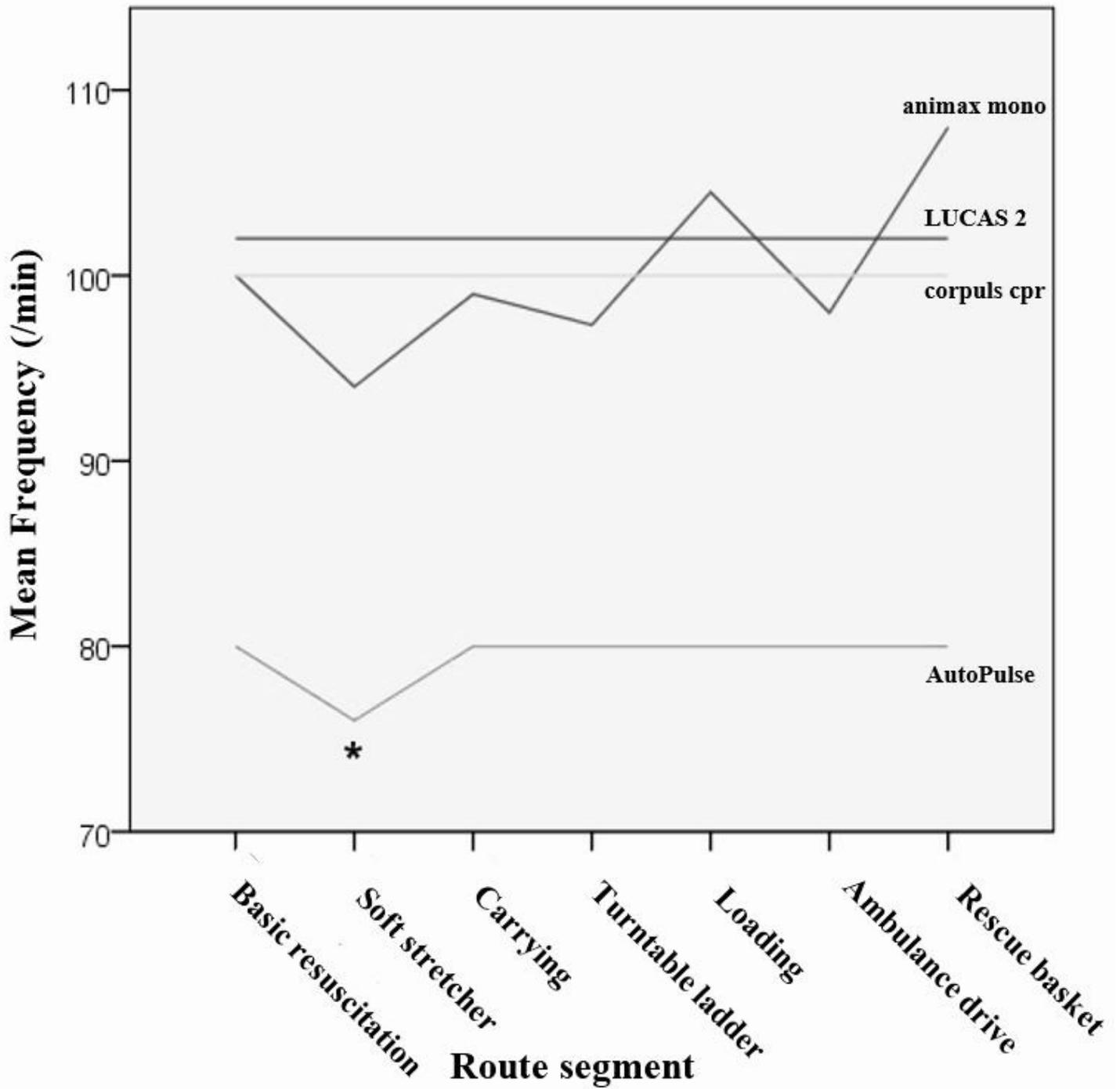


Figure 2

Mean frequency (/min) of the four mCPR device on the routes. (\*) Faulty data recording: termination after 20 seconds during the first run; hence limited information

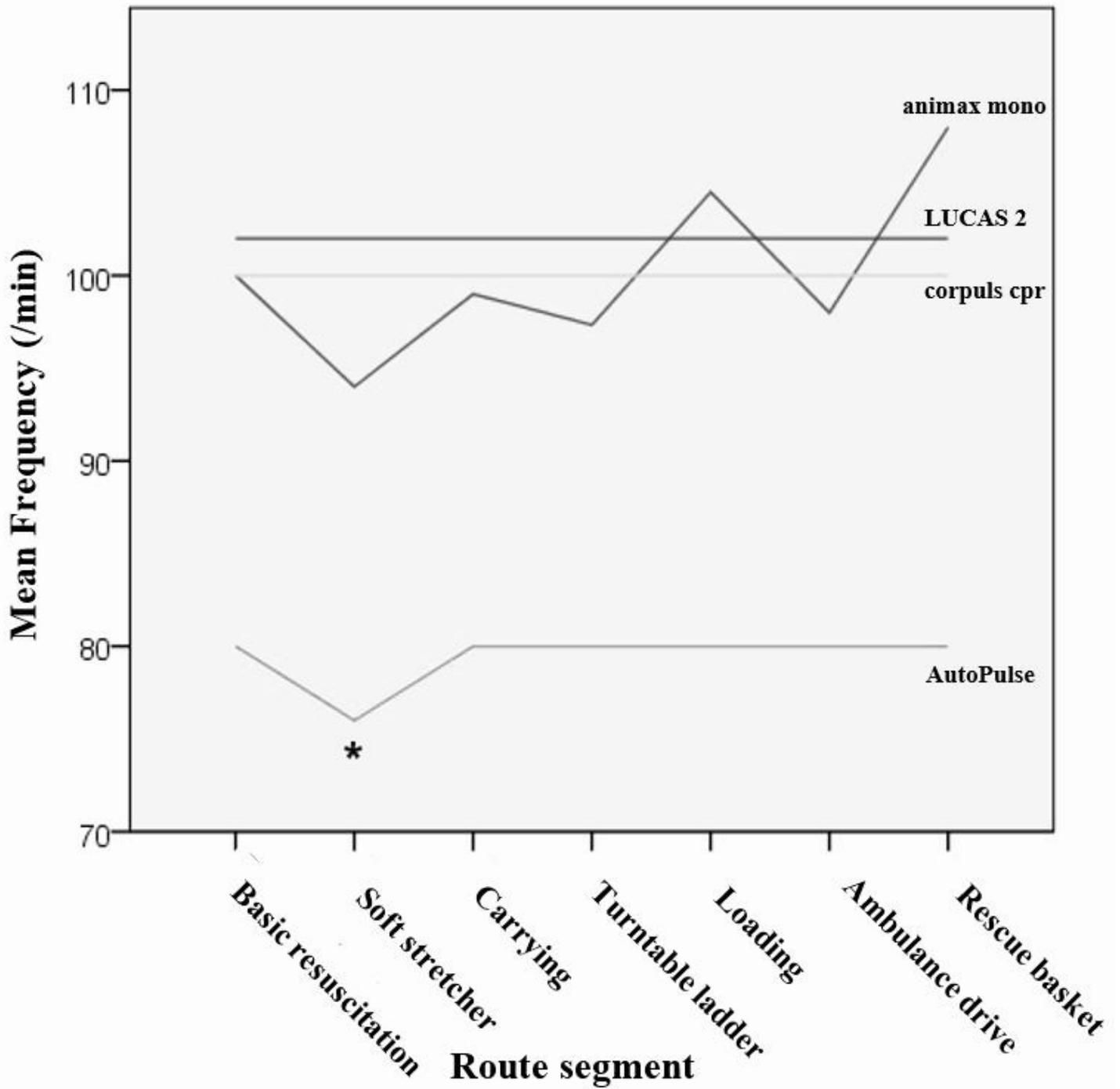


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