

Gesundheits- und Bewegungsförderung von Berufskraftfahrenden

Evaluation eines sitzintegrierten Mobilisationssystems anhand
biomechanischer, physiologischer und subjektiver
Beanspruchungsparameter

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Abkürzungsverzeichnis

BWS	Brustwirbelsäule
EEG	Elektroenzephalogramm
EMG	Elektromyogramm
LBP	Low Back Pain (Schmerzen im unteren Rücken)
Lkw	Lastkraftwagen
LWS	Lendenwirbelsäule
M.	Musculus
MVC	Maximum Voluntary Contraction (Maximale willkürliche Kontraktion)
NIRS	Nahinfrarotspektroskopie
PVT	Psychomotor Vigilance Task (standardisierter Vigilanztest)

Zusammenfassung

Langes ununterbrochenes Sitzen ist ein entscheidender Faktor physiologischer Beanspruchung von Berufskraftfahrenden. Es sorgt für Rückenbeschwerden, Schmerzen und krankheitsbedingte Arbeitsausfälle. Gleichzeitig begünstigen teilautomatisierte monotone Fahrsituationen eine zu geringe kognitive Beanspruchung, was das Risiko passiver aufgabenbezogener Ermüdung und damit verbundener Verkehrsunfälle erhöht. Aufgrund der langen Lenkzeiten sind Fernkraftfahrende dauerhaft einer sitzenden Tätigkeit ausgesetzt. Maßnahmen zur präventiven Reduktion physiologischer Beanspruchung und passiver aufgabenbezogener Ermüdung, die direkt während der Fahrt eingesetzt werden können, sind daher für diese Berufsgruppe von besonderem Interesse. In der vorliegenden kumulativen Dissertation wurden die Effekte eines sitzintegrierten Mobilisationssystems mit alternierender Luftkissenaktivität in der Sitzfläche und Rückenlehne sowohl auf physiologische als auch auf kognitive Parameter in einer Reihe von Studien mit Inner-Subjekt-Design untersucht. In einer achtwöchigen Fahrsimulatorstudie mit 16 Berufskraftfahrenden konnte gezeigt werden, dass die sitzintegrierte Mobilisationsfunktion die Bewegungsaktivität der Versuchspersonen, während der viereinhalbstündigen Fahrt, erhöht und die Muskelsteifigkeit im Brust- und Lendenwirbelbereich signifikant reduziert. Auch das subjektive Diskomfortempfinden verbesserte sich deutlich – ein Effekt, der sich objektiv im Sitzverhalten widerspiegelte. Entgegen den Erwartungen zeigte sich jedoch kein signifikanter Einfluss auf die Muskelaktivität der Rückenmuskulatur im EMG-Signal. Ein vierwöchiger Realfahrversuch mit 31 Teilnehmenden zur Untersuchung passiver aufgabenbezogener Ermüdung ergab aktivierende Effekte der Mobilisation auf die Alpha-Spindel-Rate im EEG – einem ermüdungssensitiven Parameter. Andere Vigilanzparameter zeigten hingegen keine signifikanten Veränderungen. Insgesamt zeigt das sitzintegrierte Mobilisationssystem Potenzial zur Verringerung der physiologischen Beanspruchung und der kognitiven Ermüdung von Berufskraftfahrenden während langer monotoner Fahrten und könnte somit einerseits zur Verbesserung der Arbeits- und Lebensbedingungen von Fahrenden und darüber hinaus zur allgemeinen Sicherheit im Straßenverkehr beitragen.

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1. Motivation

Berufskraftfahrende sind in ihrem Arbeitsalltag einer Vielzahl belastender Faktoren ausgesetzt, die teilweise gesundheitsschädlich sein können. Dazu zählen Bewegungsmangel, hohe körperliche und psychische Belastung sowie eingeschränkte Möglichkeiten für eine ausgewogene Ernährung (Bundesamt für Güterverkehr, 2021; Holzgreve et al., 2022). Diese Bedingungen führen dazu, dass bestimmte Erkrankungen in dieser Berufsgruppe häufiger auftreten als in anderen. Lkw-Fahrende weisen ein erhöhtes Risiko für kardiovaskuläre Erkrankungen, Krebs, Diabetes mellitus, Magengeschwüre, Bluthochdruck und Adipositas auf (Apostolopoulos et al., 2010; Crizzle et al., 2017; Laden et al., 2007; Lenk et al., 2017; Michaelis, 2008). Primär sind jedoch Erkrankungen des Muskel-Skelett-Apparates sowie Arbeitsunfälle ursächlich für Arbeitsunfähigkeitstage (Bundesamt für Güterverkehr, 2021; Tahernejad et al., 2024). Im Jahr 2024 waren Angehörige der Berufsgruppe „Führer/-innen von Fahrzeug und Transportgeräten“ laut dem Fehlzeiten-Report der Technischen Krankenkasse durchschnittlich 31,2 Tage arbeitsunfähig und damit, wie bereits in den Jahren davor, die Berufsgruppe mit den meisten Fehlzeiten (Techniker Krankenkasse, 2025). Schmerzen im unteren Rückenbereich sind laut Hakim und Mohsen (2017) und Joseph et al. (2020) die häufigste Ursache für krankheitsbedingte Ausfalltage bei Berufskraftfahrenden.

Neben langen statischen Sitzphasen, die sich negativ auf das Muskel-Skelett-System auswirken, können lange monotone Fahrsituationen zur kognitiven Ermüdung führen. Diese Form der Ermüdung stellt eine zentrale Unfallursache bei der Entstehung von Lkw-Unfällen dar (Evers & Auerbach, 2006; Müller, 2015). Die tatsächliche Zahl ermüdungsbedingter Unfälle ist schwer einzuschätzen, da die Polizei oft nur unter Ausschluss anderer Ursachen auf einen ermüdungsbedingten Unfall schließt. Müdigkeit am Steuer wird nur selten zugegeben und kann daher und aufgrund fehlender Messmethoden nur schwer erfasst werden (Evers & Auerbach, 2006). Sind Lkws in einen Unfall verwickelt, sorgt die Masse des Fahrzeugs dafür, dass andere Unfallbeteiligte meist schwerwiegender verletzt werden als die Insassen des Lkws (Heinze & Böhringer, 2021). Im schlimmsten Fall kann ein Unfall zu tödlichen Verletzungen führen. Neben den erheblichen physischen und psychischen Folgen der Unfälle können zudem hohe Sachschäden entstehen. Berufskraftfahrende sind wegen ihrer Fahrtätigkeit einem erhöhten Risiko ausgesetzt aufgrund eines Verkehrsunfalls nicht mehr arbeitsfähig zu sein und einen längeren Zeitraum auszufallen (Michaelis, 2015).

Langes Sitzen und monotone Fahrsituationen belasten nicht nur die Gesundheit der Fahrenden, sondern haben auch weitreichende Folgen für die Industrie. Ausfalltage führen zu zusätzlichen Verschärfungen der Personalknappheit und zu Umsatzminderungen (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin, 2024; Lenaerts et al., 2020). Daher sollte die Arbeitsfähigkeit und die Gesundheit von Berufskraftfahrenden auch aus wirtschaftlicher und arbeitsmedizinischer Sicht erhalten werden. Um dieses Ziel zu erreichen, ist ein Zusammenwirken verschiedener Akteure notwendig. Dazu gehören unter

anderem die Berufsgenossenschaften, die Transportunternehmen und die Kraftfahrzeugindustrie. In der vorliegenden kumulativen Dissertation soll aus bewegungswissenschaftlicher Sicht untersucht werden, ob eine speziell entwickelte sitzintegrierte Maßnahme eines Nutzfahrzeugherstellers das Potenzial hat, den negativen Auswirkungen langer statischer Sitzdauern und monotoner teilautomatisierter Fahrten entgegenzuwirken. Die Operationalisierung erfolgt über biomechanische, physiologische sowie subjektive Beanspruchungsparameter, die im Rahmen standardisierter Fahrstudien systematisch erfasst werden.

2. Physiologische und kognitive Beanspruchung von Berufskraftfahrenden

Die physiologische und kognitive Beanspruchung von Berufskraftfahrenden durch langes ununterbrochenes Sitzen und monotone Fahrsituationen stellt eine erhebliche Herausforderung dar, die sowohl die Gesundheit (Kolich et al., 2000) als auch die Leistungsfähigkeit der Fahrenden beeinträchtigen kann (Gimeno et al., 2006). Die maximale Lenkzeit und somit die Sitzdauer von Berufskraftfahrenden entspricht in Europa nach der Verordnung (EG) Nr. 561/2006 des Europäischen Parlaments und des Rates vom 15. März 2006 viereinhalb Stunden. Spätestens nach dieser Zeit muss eine 45-minütige Pause folgen, bevor eine erneute viereinhalbstündige Fahrt begonnen werden darf. Während der viereinhalbstündigen Fahrperioden sind die Fahrenden überwiegend zu einer statischen Körperhaltung gezwungen. Diese kann den Muskel-Skelett-Apparat sowohl unter- als auch überfordern und ignoriert die natürlichen, dynamischen Regulationsmechanismen des menschlichen Körpers, der nicht dafür ausgelegt ist, über längere Zeit in einer unbewegten Position zu verharren (Ludwig & Breithecker, 2008; Seiferlein & Kohlert, 2018). Für die Berufsgruppe der Berufskraftfahrenden sind lange ununterbrochene Sitzdauern unvermeidbar. Ungünstige Sitzhaltungen beeinträchtigen die Rotation des Beckens, was zu einer verminderten Lordose in der Lendenwirbelsäule und folglich zu erhöhter Krafteinwirkung auf die Bandscheiben führen kann (Lord et al., 1997). Das Sitzen in einer zusammengefallenen Haltung, in der Wissenschaft „slumped sitting“ genannt, stellt einen Risikofaktor für körperliche Schmerzen insbesondere Schmerzen im unteren Rücken (Low Back Pain, LBP) dar (Akkarakittichoke & Janwantanakul, 2017; Jung et al., 2020).

Zur Aufrechterhaltung der Sitzhaltung während der Fahrt ist die Aktivierung verschiedener Muskelgruppen nötig. Der Musculus (M.) spinae dient dabei hauptsächlich der Aufrichtung der Wirbelsäule (Faller, 2012). Außerdem gehört der M. trapezius zu den Muskeln, die während des Fahrens aktiviert werden (Balasubramanian & Adalarasu, 2007). Die Sitzhaltung wird durch anhaltende Kontraktionen dieser Muskelgruppen stabilisiert. Oft reichen hier sehr geringe Kontraktionen (< 10% der maximalen Muskelkontraktion) aus (Mork & Westgaard, 2006; van Dieën et al., 2001). Selbst bei diesen niedrigen Werten kann jedoch bei langanhaltender Dauer die periphere Blutversorgung der oberen und unteren Gliedmaßen unzureichend sein (McGill et al., 2000) und so die Nährstoffzufuhr der Muskeln und den Abbau von Abfallprodukten schwächen (Restaino et al., 2015; Thosar et al., 2014).

Das Verharren in einer statischen Sitzposition führt zu einem erhöhten Risiko für die Entwicklung von Rückenschmerzen (Bontrup et al., 2019; Lis et al., 2007; Nairn et al., 2013; Porter & Gyi, 2002). Die statische Belastung und der restringierte Blutfluss während des Sitzens können nachweislich zur Ermüdung der Rückenmuskulatur führen (Hosea et al., 1986; Jørgensen et al., 1988). Tritt diese Belastung über einen längeren Zeitraum auf, können Schäden des Muskel-Skeletts-Systems entstehen (Kolich et al., 2000). Außerdem steigt mit zunehmender Fahrdauer nachweislich das subjektive Diskomfortempfinden (El Falou et al., 2003; Waongenngarm et al., 2016) und wird mit einer erhöhten

Muskelsteifigkeit in Verbindung gebracht (Kett, 2022; Kett & Sichtung, 2020). Letzteres steht in direktem Zusammenhang mit der Entwicklung von Schmerz im unteren Rücken (Masaki et al., 2017), der die häufigste Form von arbeitsbedingten Muskel-Skelett-Erkrankungen darstellt (Ehrlich, 2003).

Neben der bereits beschriebenen physischen Beanspruchung als Folge exzessiven Sitzens kann auch die kognitive Beanspruchung ein Problem langer Sitz- und Fahrtzeiten darstellen (Gimeno et al., 2006). Studien deuten darauf hin, dass statisch-passives Sitzverhalten mit einem fortschreitenden Verlust von Aufmerksamkeit und Konzentration einhergeht (Bontrup et al., 2019; Dordel & Breithecker, 2003). Laut Carter et al. (2018) führt eine durch langes Sitzen verursachte verminderte Gehirndurchblutung zu einer Beeinträchtigung der kognitiven Leistungsfähigkeit. Die primäre Aufgabe der Fahrenden ist das Fahren. Um dieser Aufgabe gerecht zu werden, müssen Fahrende die Verkehrssituation stets überwachen, damit sie im Zweifel eingreifen können. Zur Aufrechterhaltung der Verkehrstüchtigkeit, bedarf es der Daueraufmerksamkeit der Fahrenden, die auch als Vigilanz bezeichnet wird (Gimeno et al., 2006; Pastor et al., 2006). Vigilanz beschreibt die Fähigkeit, über einen längeren Zeitraum hinweg aufmerksam zu bleiben, um seltene und subtile Veränderungen in der Umgebung wahrzunehmen (Oken et al., 2006). Diese Fähigkeit ist insbesondere bei monotonen Fahraufgaben von zentraler Bedeutung, da solche Situationen durch geringe Reizdichte und fehlende Abwechslung gekennzeichnet sind. Dieser zunehmend nicht vigilante Zustand, auch als Hypovigilanz bezeichnet, geht mit wachsenden Müdigkeits- und Schläfrigkeitsgefühlen einher (Dangelmaier & Marberger, 2003). Begriffe wie Müdigkeit, Ermüdung und Schläfrigkeit werden im alltäglichen Sprachgebrauch häufig gleichbedeutend verwendet. In der verkehrspsychologischen Forschung hingegen – wie im Modell von May und Baldwin (2009) dargestellt (s. Abbildung 1) – erfolgt eine differenzierte Betrachtung, bei der zwischen schlafbezogener und aufgabenbezogener Müdigkeit unterschieden wird.

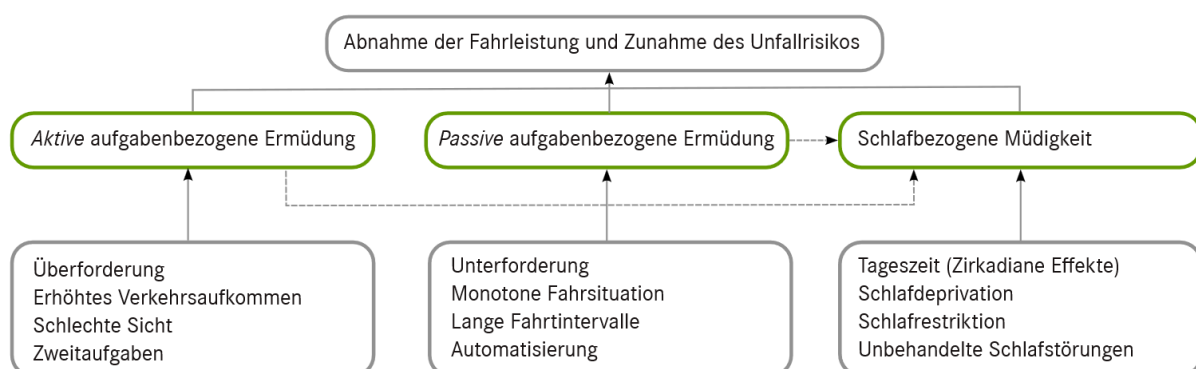


Abbildung 1: Ermüdungsmodell (nach May & Baldwin, 2009)

Je nach dem Beanspruchungsmaß der Aufgabe wird nochmals zwischen der aktiven und der passiven Ermüdung differenziert (Saxby et al., 2013). Tritt z.B. ein erhöhtes Verkehrsaufkommen, schlechte Sicht

oder eine Zweitaufgabe auf, kommt es zur Überforderung der Fahrenden. Hierbei handelt es sich nach dem Modell um eine *aktive* aufgabenbezogene Ermüdung. Die *passive* aufgabenbezogene Ermüdung wird durch die Unterforderung in monotonen Fahrsituationen und langen Fahrtintervallen induziert und kann durch eine Automatisierung der Fahraufgabe auftreten. Die schlafbezogene Müdigkeit resultiert aus der Schlafqualität jedes bzw. jeder Einzelnen und kann durch Schlafdeprivation, Schlafrestriktionen und/oder Schlafstörungen hervorgerufen werden. Auch die zirkadianen Effekte der Tageszeit können eine Rolle spielen (May & Baldwin, 2009). Wichtig ist diese Unterscheidung vor allem im Hinblick darauf, welche Maßnahmen Abhilfe schaffen können. Nur durch Schlaf selbst kann die schlafbezogene Müdigkeit verringert werden (Philip et al., 2005). Die aufgabenbezogene Ermüdung und die schlafbezogene Müdigkeit können sich gegenseitig verstärken, dadurch die Vigilanz verringern und zu einem erhöhten Unfallrisiko führen (May & Baldwin, 2009).

Die vorliegende Arbeit konzentriert sich auf die passive aufgabenbezogene Ermüdung, da diese durch die geringe kognitive Beanspruchung der Berufskraftfahrenden in deren Berufsalltag eine große Rolle spielt (Saxby et al., 2013). Diese passive aufgabenbezogene Ermüdung steht in direktem Zusammenhang mit einem erhöhten berufsbedingten Unfallrisiko (Copsey et al., 2010; Robb et al., 2008).

Hinzu kommt die zunehmende Automatisierung durch Fahrassistenzsysteme, die zu einer zusätzlichen Steigerung dieser Form der Ermüdung durch noch geringere kognitive Ansprüche im Straßenverkehr führen kann (Hancock & Verwey, 1997; Körber et al., 2015). Die vollständige Automatisierung des Straßenverkehrs erfordert noch die Überwindung vielfältiger technischer, rechtlicher und gesellschaftlicher Hürden (Viscelli, 2018). In diesen Übergangsphasen wird ein Großteil der Fahrzeuge teil- oder hochautomatisiert sein, was die Problematik der Vigilanz weiter verschärft. Daher gewinnt es zunehmend an Bedeutung, den Menschen als überwachende Instanz hinter dem Steuer dauerhaft aufmerksam und einsatzbereit zu halten (Noy et al., 2018). Angesichts der schwerwiegenden Folgen von Lkw-Unfällen und der berufsbedingten Faktoren, die Hypovigilanz begünstigen, kommt dem Erhalt der Vigilanz bei Berufskraftfahrenden eine besondere Bedeutung zu. Trotz fortschreitender Automatisierung bleibt der Mensch auf absehbare Zeit ein zentraler Bestandteil der Verkehrssicherheit (Noy et al., 2018).

3. Präventionsmaßnahmen

Zur Verringerung der physiologischen Beanspruchung und der kognitiven Ermüdung wurden bereits verschiedene Präventionsmaßnahmen innerhalb und außerhalb des Fahrzeugs untersucht. Die physiologischen Auswirkungen sedentären Verhaltens lassen sich durch körperliche Aktivität und Bewegung reduzieren (Ekelund et al., 2016; Sowah et al., 2018; Steffens et al., 2016). Zur Prävention von LBP wird empfohlen, sich regelmäßig aktiv zu bewegen (Burton et al., 2006). Laut einem systematischen Review von Ekelund et al. (2016) sind 60 bis 75 Minuten moderater körperlicher Aktivität täglich erforderlich, um die negativen Effekte langer Sitzzeiten auszugleichen. Neben klassischem Krafttraining mit freien Gewichten (Welch et al., 2015) zeigen auch Dehnübungen positive Wirkungen (Plandowska et al., 2024). Eine Studie von Zeb et al. (2025) weist insbesondere bei Berufskraftfahrenden auf den potenziellen Nutzen körperlicher Aktivität hin. Aufgrund gesetzlich vorgeschriebener Lenkzeiten und des hohen Zeitdrucks im Transportgewerbe (Sagberg et al., 2004) werden solche Maßnahme im Berufsalltag jedoch selten umgesetzt. Bei einer Befragung durch Passey et al. (2014) gaben Fernkraftfahrende an, es fehle ihnen an Zeit, Motivation und Energie für regelmäßiges Training.

Neben aktiv durchgeführten Interventionen zeigen auch passive Maßnahmen wie etwa Massagebehandlungen (Chua et al., 2016; Eriksson Crommert et al., 2015; Fraser & Kerr, 1993) sowie gezielte punktuelle Selbstmassagen mittels Faszienrollen, eine Wirksamkeit in der Reduktion muskulärer Steifigkeit (Kett, 2022; Kett & Sichtung, 2020). Im Kontext sitzender Büroarbeiten wurden bereits verschiedene Ansätze zur Prävention von LBP untersucht. So kann das Vermeiden der „slumped sitting“-Position – einer ausgeprägten Kyphose im Lenden- und Brustwirbelsäulenbereich (LWS- und BWS-Bereich) – das Risiko haltungsbedingter Rückenschmerzen senken (Lee & Yoo, 2011). Allerdings ist eine ideale Sitzposition über längere Zeit schwer aufrechtzuerhalten (Hirao et al., 2017) und kann bei dauerhafter Einhaltung sogar schädlich sein (Bontrup et al., 2019; Coenen et al., 2017). Daher gilt es als sinnvoller, regelmäßig zwischen verschiedenen Sitzhaltungen zu wechseln. Bürostühle, die dynamische Bewegungen ermöglichen, zeigen in diesem Zusammenhang deutliche Vorteile gegenüber statischen Sitzmöbeln (Frey et al., 2021; Tanoue et al., 2016; van Dieën et al., 2001).

Auch in der Automobilindustrie spielt die Optimierung der Fahrzeugsitze eine zentrale Rolle. Dabei steht häufig der subjektiv empfundene Sitzkomfort als Qualitätsmerkmal im Fokus (Romelfanger & Kolich, 2019; Smith et al., 2006). Darüber hinaus wurden jedoch auch sitzintegrierte Systeme zur Reduktion gesundheitlicher Beschwerden während der Fahrt erforscht. Ziel dieser Interventionen ist es, durch dynamische Stimulation der Insassen die muskuläre Inaktivität zu unterbrechen, die Durchblutung zu fördern und die Belastung des Muskel-Skelett-Systems bei langen Sitzzeiten zu verringern. Dazu zählen bewegliche Sitzflächen und Rückenlehnen (Lee et al., 2020; Lengsfeld et al., 2000; Pellettiere et al., 2006; van Deursen et al., 2000; Varela et al., 2017), variable oder pulsierende Lordosenstützen (Kolich

et al., 2001) sowie sitzintegrierte Massagefunktionen (Durkin et al., 2006; Franz et al., 2011). Diese pneumatischen Massagesysteme beschränken sich jedoch entweder ausschließlich auf den Oberkörper oder auf den Lendenwirbelsäulenbereich. Im Nutzfahrzeuggestrich untersuchten Cardoso et al. (2018) einen Lkw-Fahrersitz mit einem konturierten Schaumstoff-Sitzkissen und einer ebensolchen - Rückenlehne. Der Schaumstoff verteilte das Körpergewicht der Insassen auf eine größere Fläche, was nicht nur den Komfort verbesserte, sondern auch die Aufmerksamkeit der Versuchspersonen erhöhte.

Während ergonomische Sitzlösungen primär auf die Reduktion physischer Belastungen abzielen, gewinnen ergänzende Maßnahmen an Bedeutung, die auch der kognitiven Ermüdung in monotonen Fahrsituationen entgegenwirken. Zur Minderung der Unterforderung der Berufskraftfahrenden und der damit verbundenen passiven aufgabenbezogenen Ermüdung in monotonen Fahrsituationen, wurden bereits verschiedene vitalisierende Maßnahmen untersucht (Gaspar et al., 2017; Gimeno et al., 2006). Dazu zählen die Zufuhr von kalter Luft (Schmidt & Bullinger, 2019), Menthol-Beduftung (Popp, 2005; Rothe et al., 2013), die Einnahme von Koffein und Taurin (de Valck & Cluydts, 2001; Mets et al., 2011), der Einsatz von biologisch wirksamem Licht (Popp, 2005; Popp et al., 2024; Schüler et al., 2020) sowie die taktile Stimulation durch Vibration (Greschner & Spath, 2011) oder bewegliche Sitzkomponenten wie Sitzfläche, Rückenlehne und Lordosstütze (Lee et al., 2020). Auch sogenannte Zweitaufgaben während der Fahrt – etwa Geschwindigkeitsveränderungen, Spurwechsel, Gaming, Telefongespräche oder Reaktionsaufgaben – haben sich als wirksam zur Aufrechterhaltung der Aufmerksamkeit erwiesen (Anton et al., 2008; Gimeno et al., 2006; Lampe & Deml, 2022; Neubauer et al., 2014; Schmidt et al., 2011; Schömig et al., 2015).

Die Maßnahmen weisen jedoch unterschiedliche Vor- und Nachteile auf. So zeigte die Zufuhr kalter Luft lediglich kurzfristige Effekte auf die subjektiv wahrgenommene Ermüdung (Schmidt & Bullinger, 2019), während die Menthol-Beduftung leicht positive Effekte auf objektive Parameter zeigte – allerdings nur bei nächtlichen Fahrten (Popp, 2005; Rothe et al., 2013). Die regelmäßige Einnahme größerer Mengen Koffein und Taurin kann gesundheitsschädlich sein (Beiglböck, 2016) und biologisch wirksames Licht kann bei Dunkelheit zu Blendungen führen (Ottersbach, 2017). Bei der Anwendung von Zweitaufgaben besteht das Risiko einer Ablenkung von der eigentlichen Fahraufgabe (Neubauer et al., 2014). Im Vergleich dazu zeigt die taktile, sitzintegrierte Stimulation zur passiven Mobilisation der Insassen das größte Potenzial unter den untersuchten Maßnahmen. Sie erfordert keine aktive Beteiligung der Fahrenden und birgt somit ein geringes Ablenkungsrisiko (Lee et al., 2020). Eine Fahrstudie konnte mittels Elektroenzephalografie (EEG) positive Effekte eines Massagesitzes auf die Vigilanz in langanhaltenden monotonen Fahrsituationen nachweisen. Subjektiv berichteten die Teilnehmenden zudem von einer gesteigerten Leistungsfähigkeit und Fitness (Rothe et al., 2013). Die von Rothe et al. (2013) untersuchte Massagefunktion basiert auf sieben Luftkissen in der Rückenlehne, die die Wirbelsäule aussparen und durch wechselndes Be- und Entlüften eine wellenartige Massage erzeugen.

Als Weiterentwicklung dieses Konzepts entstand im Rahmen der Masterarbeit *Konzeption und prototypischer Aufbau eines Lkw-Fahrersitzes zur Gesundheitsprävention von Berufskraftfahrern* von Schneider (2017) der in dieser Arbeit evaluierte Mobilisationssitz. Dieser stimuliert die Insassen durch das alternierende Aufblasen und Entleeren von vierzehn Luftkissen in der Rückenlehne sowie vier Luftkissen im Sitzkissen. Die Mobilisationsprogramme wurden in Zusammenarbeit mit Fachkräften aus Sportwissenschaft, Physiotherapie, Orthopädie und Chirurgie entwickelt. Ziel war es, die physiologische Beanspruchung sowie die passive aufgabenbezogene Ermüdung von Fernkraftfahrenden möglichst effektiv zu reduzieren.

Die Mobilisationsprogramme setzen sich aus vier unterschiedlichen Mobilisationssequenzen zusammen, die sich hinsichtlich der aktivierten Luftkammern, des zeitlichen Ablaufs und der Intensität unterscheiden:

- Die *asymmetrische Gehbewegung* erzeugt eine seitenalternierende Bewegung von Oberkörper und Becken in entgegengesetzter Richtung.
- Die *symmetrische Gehbewegung* kombiniert die seitenalternierende Bewegung von Oberkörper und Becken in die gleiche Richtung.
- Die *Mobilisationswelle* aktiviert nacheinander die Luftkissen im Lenden-, Brust- und Schulterbereich.
- Das *Beckenkippen* stimuliert zunächst den vorderen, dann den hinteren Sitzkissenbereich sowie den Lendenbereich.

Die Funktionsweise des Mobilisationssitzes ist unter den Patentnummern DE 10 2018 000 765 A1 und DE 10 2019 002 373 A1 beim Deutschen Patentamt dokumentiert. Im Unterschied zu anderen Systemen handelt es sich hierbei um ein pneumatisches System, das sowohl die Rückenlehne als auch das Sitzkissen umfasst.

4. Herleitung der Forschungsfragen

Infolge der in Kapitel 2 beschriebenen physiologischen Beanspruchung weisen Berufskraftfahrende eine erhöhte Prävalenz für Muskel-Skelett-Erkrankungen auf (Joseph et al., 2020; Tahernejad et al., 2024). Vor diesem Hintergrund wird in der vorliegenden Arbeit ein sitzintegriertes Mobilisationssystem als potenzielle Gegenmaßnahme zur Reduktion dieser physischen Beanspruchung untersucht. Kapitel 3 zeigte bereits, dass sich die negativen Auswirkungen sedentären Verhaltens durch dynamisches Sitzen (Lengsfeld et al., 2000; van Deursen et al., 2000) und kontinuierliche passive Bewegungsreize (Pellettiere et al., 2006; van Deursen et al., 2000) verringern lassen. Die durch Luftkissen erzeugten Bewegungen des Mobilisationssystems könnten somit einen präventiven Effekt auf die Entstehung von Muskel-Skelett-Erkrankungen haben. Erste Vorstudien zur Programmentwicklung zeigten eine positive subjektive Bewertung des Sitzkomforts (Schneider, 2017). Aufbauend auf diesen Erkenntnissen wird in der vorliegenden Arbeit das neu entwickelte Mobilisationssystem hinsichtlich seines Einflusses auf die physiologische Beanspruchung von Berufskraftfahrenden evaluiert.

Forschungsfrage 1: *Verringert das sitzintegrierte Mobilisationssystem die physiologische Beanspruchung von Berufskraftfahrenden?*

Neben der physischen Belastung stellt auch die kognitive Unterforderung in monotonen Fahrsituationen eine zentrale Herausforderung dar. Wie in Kapitel 3 erläutert, kann dynamische Bewegung im Sitz eine wirksame Maßnahme zur Reduktion passiver aufgabenbezogener Ermüdung darstellen (Lee et al., 2020; Pellettiere et al., 2006; Rothe et al., 2013). Angesichts der zunehmenden Automatisierung im Straßenverkehr und der damit verbundenen Relevanz der Vigilanzproblematik wurde in dieser Arbeit zudem untersucht, ob das Mobilisationssystem unter realen Fahrbedingungen im Lkw zur Verbesserung kognitiver Leistungsparameter beitragen kann.

Forschungsfrage 2: *Verringert das sitzintegrierte Mobilisationssystem die kognitive Ermüdung von Berufskraftfahrenden?*

5. Eigene Beiträge zur Evaluation eines sitzintegrierten Mobilisationssystems anhand biomechanischer, physiologischer und subjektiver Parameter

Aus den theoretischen Überlegungen und den abgeleiteten Forschungsfragen ergibt sich folgendes Forschungsprogramm zur Evaluation des sitzintegrierten Mobilisationssystems (s. Abbildung 2).

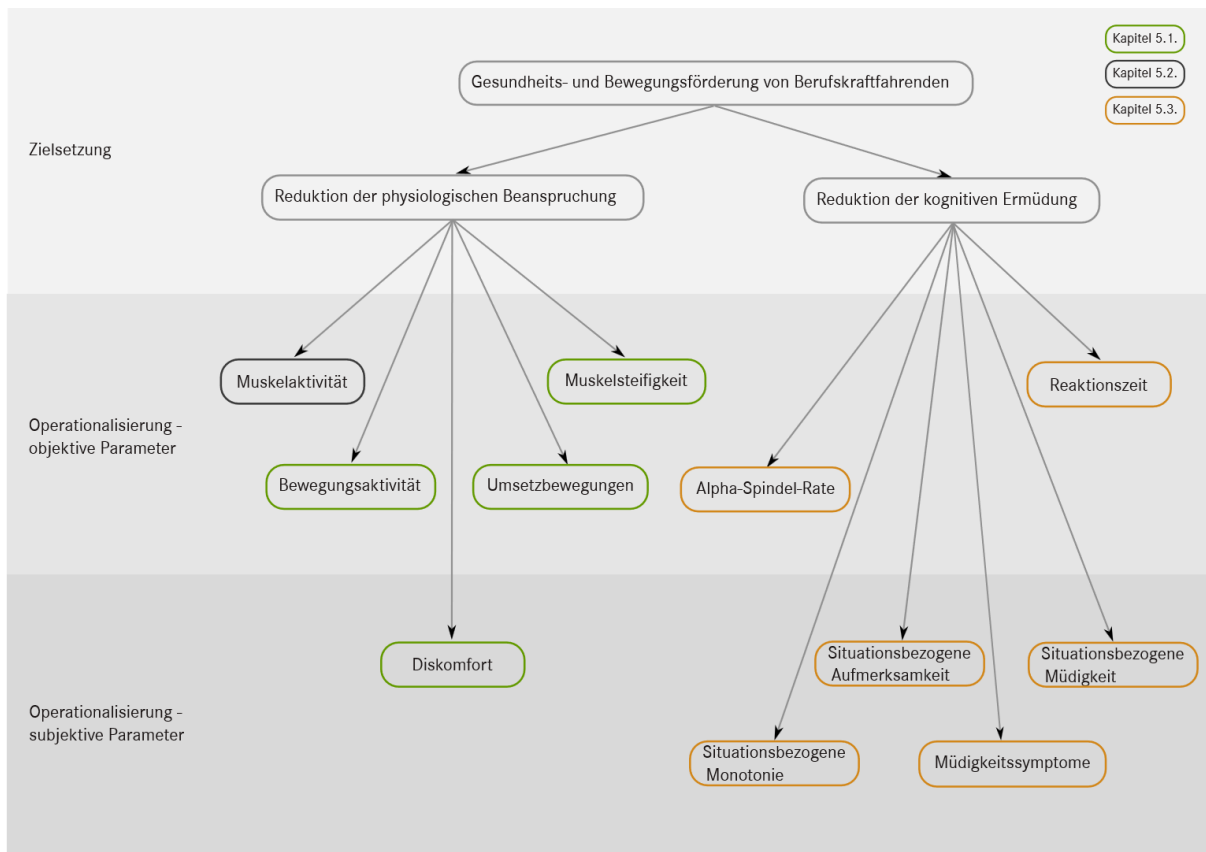


Abbildung 2: Grafische Darstellung des Forschungsprogramms zur Evaluation eines sitzintegrierten Mobilisationssystems anhand objektiver und subjektiver Parameter

Das übergeordnete Ziel der vorliegenden Arbeit ist die Gesundheits- und Bewegungsförderung von Berufskraftfahrern. Basierend auf den theoretischen Grundlagen aus Kapitel 2 und Kapitel 3 wird durch die Integration der Mobilisation eine Reduktion sowohl der physiologischen Beanspruchung als auch der kognitiven Ermüdung erwartet.

Zur Beantwortung der ersten Forschungsfrage – *Verringert das sitzintegrierte Mobilisationssystem die physiologische Beanspruchung von Berufskraftfahrern?* – wurde eine Fahrsimulatorstudie im Inner-Subjekt-Design durchgeführt. Dabei wurde untersucht, ob die langanhaltende Fahraufgabe sowie das Be- und Entlüften der Luftkissen im Sitz zu Veränderungen biomechanischer, physiologischer und subjektiver Parameter führen. Eine erhöhte Bewegungsaktivität infolge der Mobilisationsfunktion könnte sich positiv auf den Körper auswirken (van Deursen et al., 2000; van Dieën et al., 2001). Es wird angenommen, dass subjektiv wahrgenommener Diskomfort sowie die Zahl der Umsetzungsbewegungen mit

zunehmender Sitzdauer ansteigen (Bendix et al., 1985; Fenety et al., 2000; Varela et al., 2017). Veränderungen in der Aktivität der Rückenmuskulatur über die Zeit können Rückschlüsse auf Schmerzentwicklung und Diskomfortempfinden geben (de Looze et al., 2003). Der Diskomfort der 16 Versuchspersonen wurde sowohl subjektiv mittels Fragebögen als auch objektiv über die Erfassung von Umsetzbewegungen als indirektes Maß erfasst (Mansfield et al., 2017). Masaki et al. (2017) zeigen, dass Diskomfort und Schmerzentwicklung bei langem Sitzen mit einer erhöhten Muskelsteifigkeit einhergehen. Daher wurde überprüft, ob die viereinhalbstündige simulierte Fahrt zu einer Zunahme der Muskelsteifigkeit im Brust- und Lendenbereich führt und ob die Mobilisationsfunktion diesen Effekt beeinflussen kann.

Zur Beantwortung der zweiten Forschungsfrage – *Verringert das sitzintegrierte Mobilisationssystem die kognitive Ermüdung von Berufskraftfahrenden?* – wurde ein realer Fahrversuch im Inner-Subjekt-Design unter standardisierten Bedingungen durchgeführt. Dabei wurden sowohl physiologische als auch subjektive Parameter erfasst und zwischen Mobilisations- und Kontrollbedingung verglichen.

Die neurophysiologische Alpha-Spindel-Rate gilt als sensitivster Parameter zur Erfassung des Vigilanzdekrements in Fahrstudien (Schmidt, 2010) und wurde während der zweistündigen teilautomatisierten Fahrt kontinuierlich mittels eines mobilen EEGs aufgezeichnet. Zusätzlich wurde die Reaktionszeit der Versuchspersonen vor und nach den Fahrten mithilfe des *Psychomotor Vigilance Task* (PVT) ermittelt. Dieser standardisierte Vigilanztest nach Dinges und Powell (1985) zeichnet sich durch hohe Reliabilität, Vorhersagevalidität und geringe Lern- oder Übungeffekte aus (Basner et al., 2018). Der Test bestand darin, auf das plötzliche Erscheinen einer aufwärts zählenden Zahlenreihe Reizes auf einem Laptop so schnell wie möglich zu reagieren, indem die Versuchspersonen eine Taste auf der Tastatur drückten. Dabei wurde die Reaktionszeit gemessen. Ergänzend wurden während der Fahrt subjektive Einschätzungen zur situationsbezogenen Aufmerksamkeit, Monotonie und Müdigkeit erhoben sowie Müdigkeitssymptome vor und nach der Fahrt erfasst.

Aus den theoretischen Überlegungen und den durchgeführten Studien sind insgesamt drei wissenschaftliche Beiträge hervorgegangen, die in peer-reviewten Fachzeitschriften veröffentlicht wurden.

5.1. Auswirkungen eines sitzintegrierten Mobilisationssystems auf die Bewegungsaktivität, Muskelsteifigkeit und den Diskomfort von Fernfahrenden während einer 4,5-stündigen simulierten Fahraufgabe

Effects of a seat-integrated mobilization system on long-haul truck drivers motion activity, muscle stiffness and discomfort during a 4.5-hour simulated driving task

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Abstract

Objective: The aim of this study is to evaluate the effects of a seat-integrated mobilization system on motion activity, muscle stiffness and discomfort during prolonged driving.

Method: During a 4.5-hour driving task, motion activity, muscle stiffness and discomfort (measured subjectively and objectively) of long-haul truck drivers were determined and compared intra-individually in a test condition with mobilization (seat-integrated stimulation) and a control condition under standardized conditions in a simulated driving study ($N = 16$).

Results: In the experimental condition, participants showed a significantly increased motion activity and a reduced muscle stiffness compared to the control condition. Furthermore, discomfort occurred significantly more frequently in the control condition.

Conclusion: The mobilization system increased motion activity and reduced discomfort as well as muscle stiffness. Therefore, it provides considerable potential to counteract negative effects of prolonged sitting and to promote truck driver's health.

Keywords

Sedentary behavior

Low back pain

Truck drivers

Dynamic sitting

Health prevention

Discomfort

1. Introduction

Freight transport is a key function of our modern industrialized society (Baier 2012). According to eurostat (2021), the dominant mode in the European Union (EU) is the transportation on the road: “In 2019, road freight transport accounted for 76.3 % of the total inland freight transport, followed by rail and inland waterways transport (17.6 % and 6.1 % respectively)”. Due to the growing population, global trade in goods is likely to rise more than threefold to US\$ 27 trillion in 2030. Therefore, the logistics industry will become ever more relevant likewise (PwC 2012).

A need of qualified drivers is obvious due to the high demand for transportation and to the fact that driverless trucks are not yet commercialized (Wrenn 2017). However, challenging working conditions, further exacerbated due to COVID-19, a lack of trained drivers and difficulties attracting women and young people to the profession are reasons for an increasing shortage of drivers (International Road Transport Union 2021). The International Road Transport Union survey (2021) indicates driver shortage to soar: European companies expected a 17 % shortfall in drivers in 2021.

To handle the shortage of drivers, promoting drivers’ health is an essential issue: According to the *Techniker Krankenkasse*, a health insurance in Germany, professional drivers were, with 25.7 sick days, the occupational group with the highest sick-leaves in 2020 (Techniker Krankenkasse 2021). A study of the *National Institute for Occupational Health and Safety* (NIOHS), conducted in the US in 2014, found a constellation of chronic disease risk factors to be present among long-haul truck drivers including hypertension, high cholesterol, obesity, smoking, physical inactivity, and sleep deprivation (Sieber et al. 2014).

Long uninterrupted sitting times, to which truck drivers are exposed, are associated with an increased risk of diabetes and cardiovascular disease (Wilmot et al. 2012). Furthermore, it may affect drivers’

performance because of the negative impact on cognition (Voss et al. 2014). Prolonged sitting with uncomfortable postures and static muscle load also implies a risk of developing discomfort (Mansfield et al. 2017) and low back pain (LBP) (Mozafari et al. 2015; van Dieën et al. 2001). Diseases of the musculoskeletal system are a major reason for absenteeism of professional drivers (Taylor and Dorn 2006).

Typically, discomfort and pain development are affiliated with increased muscle stiffness: For medical workers it has been shown that muscle stiffness of the lumbar multifidus was significantly higher in participants with LBP compared to healthy participants (Masaki et al. 2017). Furthermore, a study by Kett and Sichtung (2020) showed a significant increase in stiffness of the lumbar and thoracic spine muscle of office workers after a sitting period of 4.5 hours. This is explained by stress-relaxation (Adams and Dolan 1996) in the spine's posterior tissues or viscoelastic creep (McGill and Brown 1992) while sitting in a sustained flexed posture.

From a health's perspective an effective intervention would be to reduce the time sitting or to break up long periods of sitting (Benatti and Ried-Larsen 2015; Galinsky et al. 2000). In the office context, it is common to counteract musculoskeletal complaints with the implementation of a sit-stand workstation (Husemann et al. 2009). However, with regard to professional drivers, the motivation for breaks beyond driving time regulations is very low because the increased use of just-in-time delivery has put additional pressure on drivers to meet their tight schedules (Saltzman and Belzer 2003). Accordingly, truck drivers are often bound to long sitting durations.

Postural changes during the sitting period are a natural body response to compensate discomfort by relieving the perceived pressure of compressed body parts (Waongenngarm et al. 2020). Therefore, repositioning movements while sitting are typically performed when discomfort reaches a certain level (Maradei et al. 2015; Fujimaki and Noro 2005; Na et al. 2005).

A longitudinal study of Hamberg-van Reenen et al. (2008) indicated that participants experiencing discomfort had a higher risk of injuries three year later. To prevent the development of musculoskeletal discomfort in an early stage, seat-integrated movements might be an effective intervention: As stated by van Dieën et al. (2001), movable chairs also may offer advantages compared to fixed chairs with respect to trunk loading. In the automotive context, passive movements in the seat itself were well received (Varela et al. 2019). In 2006, Durkin et al. showed beneficial effects of a lumbar massage system in car seats to reduce discomfort and prevent muscle fatigue during a one-hour simulated driving task. Positive effects of dynamic passive stimuli while sitting are also described by van Deursen et al. (2000) and Pellettiere et al. (2006). Movements in the seat were found to improve the nutrition supply of the disc through low-frequent pressure changes (van Deursen et al. 2001). Tissue stimulation by a massage treatment (Eriksson Crommert et al. 2015; Fraser and Kerr 1993; Chua et al. 2016) or a self-

massage using a foam roller (Kett and Sichtung 2020) can also be effective interventions to reduce muscle stiffness values.

The aim of this study was to investigate truck driver's motion activity, muscle stiffness and discomfort during a simulated 4.5-hour driving task with and without a seat-integrated mobilization system. We used a seat-integrated mobilization system generating dynamic stimulation by inflating and deflating air cushions in the backrest and in the seat pan. Due to the alternating movements of the air cushions of the seat-integrated mobilization system we expected higher motion activity in the mobilization condition compared to the control condition. Furthermore, the applied pressure and friction on the underlying tissues due to the alternating motion of the air cushions should had beneficial effects on the stiffness of the lumbar and thoracic back muscles. On the other hand, we expected the truck drivers to feel less subjective discomfort and therefore show fewer postural changes within the mobilization condition. The study at hand was conducted to verify and substantiate these assumptions and to clarify the potential of the mobilization system as a seat-integrated intervention.

2. Material and Methods

2.1. Participants

Sixteen male professional truck drivers (age: $M = 42$ years, range: 24 - 57 years, weight: $M = 92$ kg, range: 75 - 119 kg, height: $M = 181$ cm, range: 172 - 192 cm, BMI: $M = 28$, range: 23 - 36) participated in two simulated driving sessions for two consecutive days. The average driving distance was approximately 94,400 km/58,700 miles per year which corresponds to a regular driving practice in Europe (Stanton 2020). Due to the requirements of the measurement methods participants with a BMI over 35 could not be included in the study. Furthermore, we recruited drivers with a daily sitting duration of at least 4.5 hours per day. Another requirement was a daily sitting duration of at least 4.5 hours per day. We expected long-haul truck drivers to behave differently in their sitting pattern since the long sitting time represents their everyday life. Since only 2 % of truck drivers globally are women (International Road Transport Union 2021), only men were recruited to participate in the present study. All participants were informed about the aims and risks of the experiments and gave their written consent. The study was approved by the ethic committee of the Daimler AG and conducted according to the latest declaration of Helsinki.

2.2. Mobilization Seat

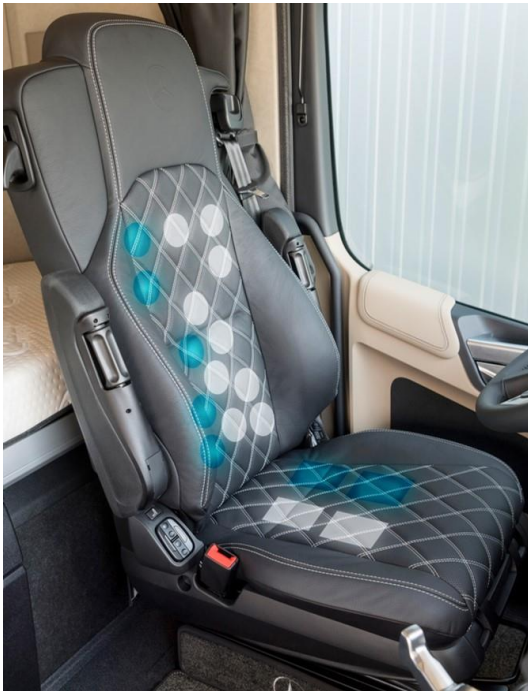


Figure 1: Mobilization Seat.

The *Mobilization Seat* (Fig. 1) generates dynamic stimulation by inflating and deflating 14 air cushions in the backrest and four air cushions in the seat pan. It was developed in the research department of the Mercedes-Benz AG and has been published under number DE 10 2018 000 765 A1. Its programs consist of four mobilization sequences in which the air cushions move alternately: asymmetrical walking movement, symmetrical walking movement, pelvic tilt and a wave movement on the backrest. A one-hour mobilization program consists of varying sequences for 34 minutes and of breaks without mobilization. This seat intervention was developed iteratively with the aim to promote dynamic sitting and to prevent negative effects of prolonged sitting on the musculoskeletal system and on the vigilance of the drivers.

2.3. Experimental Design, Materials and Procedure

To standardize the driving situation, the experiment was conducted under simulated driving conditions. Due to inter-individual differences in discomfort sensitivity (Peng et al. 2017) and muscle stiffness (Orner et al. 2018), the study was conducted with a within-subject-design. All participants underwent two experimental conditions on different survey days, consisting of a control condition and an experimental condition. The experimental condition consisted of the activation of the *Mobilization Seat*, whereas the control condition was masked by a feigned scenting of the driver's cabin. The participants ran through these test conditions in a randomized order. Thus, it could be ruled out that differences between the conditions are caused by the order in which the subjects went through the conditions. In each condition, sitting duration was 4.5 hours, which is based on the legally prescribed driving times of

professional drivers in accordance with Regulation (EC) No 561/2006 of the European Parliament and of the Council of 15 March 2006.

The participants arrived at the lab at 8:30 a.m. on both survey days. The preparation (SARS-CoV-2 test, demographic questionnaire, pre-measurement of the muscle stiffness, attachment and calibration of the measurement technologies) took about three hours, the sitting duration 4.5 hours and the subsequent follow-up about half an hour. This resulted in a total duration per participant and survey day of eight hours i.e., a duration of 16 hours for both survey days. During a subsequent phase of test sitting, the participants were instructed in the truck driving simulator and were able to individually adjust seat and steering wheel settings.

The experimental condition was a monotonous driving task. The driving simulator used in the study was a static truck driving simulator. The activations of the air cushions of the *Mobilization Seat* were visualized on a separate monitor. *Logitech's G29* steering wheel and pedal unit featured a 900-degree steering angle, force feedback, and a nonlinear brake pedal. The steering wheel differed in diameter from a truck steering wheel but allowed all functions that were necessary for the driving task. The driver's seat and steering wheel could be adjusted analogously to the truck environment. The setup did not include a gear lever, as the simulation drive took place with automatic gearshift. The *Euro Truck Simulator 2* simulation software was installed on a separate computer. *Euro Truck Simulator 2* is a truck simulation developed by SCS Software. The participants were able to follow the simulation drive via a separate monitor in the direct field of view. The investigators monitored the experiment out of the participant's sight in order to bind potential conversations and eliminate a source of distractions and movements. The experimental setup is shown in Fig. 2.



Figure 2: The experimental setup including the static truck simulator.

At the beginning of the sitting time, participants were asked to rate their discomfort on a tablet (*Galaxy TabA*, Samsung). Following this, the first of four driving sections (each one hour) started. After each one-hour driving section discomfort was queried and the measurement records were saved. Still sitting, the participants were able to drink and eat something during the breaks. Including these driving breaks, the participants were sitting continuously for 4.5 hours. After the sitting period and the post-measurement of the muscle stiffness, the measurement equipment was removed. As a final step, an acceptance questionnaire was filled out. For the comparability of the test conditions, it was necessary that all participants complete the same route in every condition. A monotonous driving situation was chosen. The simulation drive took place exclusively on the highway in order to avoid potential movements due to stops, curves and shunting processes.

2.4. Motion Activity

To record the participant's motion activity during the simulated 4.5-hour driving task a full-body human motion capture system by Xsens Technologies B.V., Netherlands was used. The system consists of a recording software called *MVN Analyze* and a full-body *MVN Link* suit with 17 wired inertial and magnetic trackers. To track the motion, the software defines a biomechanical model of the human body consisting of 23 body segments and displays an animated avatar which follows the human movements. Advanced

algorithms enable an accurate estimation of the individual body parts position, orientation and joint angles (Schepers et al. 2018). In a study conducted by Janson and Wedmark (2018), a similar Xsens system (*MVN Awinda*) was used to quantify sitting postures in cars. The authors verified the accuracy of the Xsens system by comparing it to a recognized verification method and stated that both systems correspond well (Janson and Wedmark 2018).

In this study we focused on three joint angles: the joint angle *vertical-T8*, which describes the angle between the trunk and a virtual vertical axis that is derived from the gravity vector. We also considered the angles between the pelvis and both upper legs, which are labeled as *hip angles* (Xsens Technologies B.V. 2021). Fig. 3 shows the flexion-extension component of these joint angles with the biomechanical model of the avatar. We assume these angles best describe participants' seat fidgets and movements while driving, which include movements of the lower limbs, movements of the torso and whole-body movements (Tatsuno and Maeda 2019).

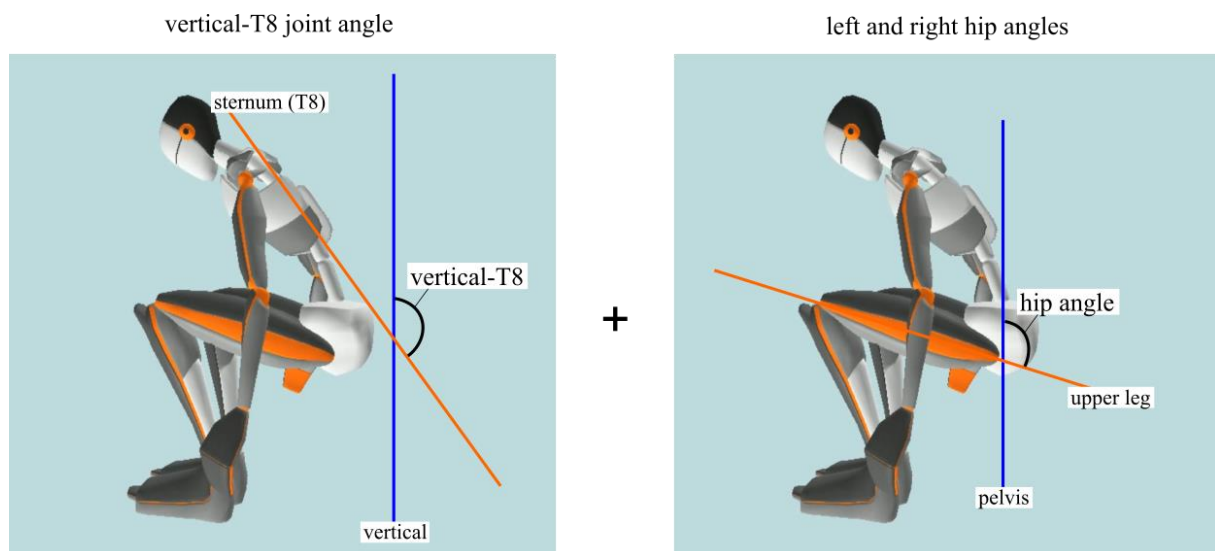


Figure 3: Xsens joint angles vertical-T8, left hip and right hip to describe participants' movements. Avatar extracted from *MVN Analyze*. Information adapted from Xsens Technologies B.V. (2021).

The joint angles sensor data was downsampled from the native update rate of 240 Hz to an output data rate of 50 Hz after the recording. For this, we used a custom script application programmed in the general-purpose programming language *Python*. We refer to this application as the processing pipeline; it performs the following two consecutive steps:

1. Downsampling
2. Calculation of motion activity indices

Since we are not expecting high dynamic movements of the participants, we assume that an output rate of 50 Hz is a reasonable tradeoff between describing human motions without information loss and manageable file sizes. Another related motion capture system by Xsens (*MVN Awinda*) uses a similar update rate of 60 Hz and does not target high dynamic movements as well (Schepers et al. 2018).

To quantify motion activity, we calculated the so-called *motion timeline*, which we define as followed:

$$E_T(t) = \sum_i^9 \text{abs}(\dot{P}_i(t))$$

The variable $P_i(t)$ is equal to the value of the i -th joint angle component at time t . According to Xsens' documentation, each joint angle consists of three components:

1. Flexion-extension
2. Lateral bending (vertical-T8) or abduction-adduction (hip angles)
3. Axial bending (vertical-T8) or internal-external Rotation (hip angles)

The upper bound of summation equals 9 for all three components of the joint angles vertical-T8, left hip and right hip. The mathematical derivative of $\dot{P}_i(t)$ indicates changes in the joint angles which correspond to body movements. The derivative also eliminates the signal offset, which compensates for possible sensor drifts of the Xsens system. By regarding only absolute values, we eliminate the orientation information from the joint angles, since we are only interested in general body activity. Based on the motion timeline, we derived the *motion score* E_S , which is a single, time-independent value for the whole timeline:

$$E_S = \text{mean}(E_T(t))$$

The motion score implies all movements of the participants including possible movements induced by the seat-integrated mobilization and movements initiated by muscle activity like postural changes. For further analysis, the motion score was calculated over the 4.5-hour driving task to quantify a person's motion activity for each condition.

2.5. Discomfort

In addition to the analysis of the motion activity, this study aimed to measure the experienced discomfort level. Discomfort is traditionally evaluated subjectively using rating scales, but there are also objective methods which quantify discomfort indirectly, such as measurements of posture, measurements of stature loss (spinal shrinkage) and estimations of muscle activation and muscle fatigue by electromyography (EMG) (de Looze et al. 2003). In contrast to the recording of the discomfort by means of questionnaires, objective methods continuously record the discomfort, since it is dynamic in nature. In applied research, whole-body movements represent an indirect objective measurement of discomfort (Mansfield et al. 2017) which increase significantly with time sitting (Fenety et al. 2000; Varela et al. 2019; Bendix et al. 1985). Hermann and Bubb (2007 - 2007) explain the purpose of the postural movements as a pressure relief of the compressed body parts with hampered blood flow.

For analyzing postural changes as an indirect measurement of sitting discomfort we used the calculated motion timeline extracted out of the motion capture data. Clearly recognizable peaks indicate increased

motion activity. As with Sammonds et al. (2017), each peak or movement was classified according to their size post trial via a full body recording by two independent experimenter: movement of the limbs (Type 1), movement of the torso (Type 2) and whole-body movement (Type 3). Since Type 3 movements are not connected with the driving task itself, only these movements were considered an indication for discomfort and were calculated manually in the present study. The number of whole-body movements served as a measure of discomfort. The advantage of using the motion capture system in contrast to an exclusive video recording is that there is no continual observation by an investigator needed (Sammonds et al. 2017) due to peak detecting in the movement timeline extracting out of the data.

In addition to the objective measurements, the experienced discomfort was queried using a visual analogue scale (VAS) (Klimek et al. 2017). The scale used was a 100 mm long straight horizontal line. The ends were defined as the extreme limits of the discomfort orientated from the left (*complete absence of discomfort*) to the right (*maximum imaginable level of discomfort*). The participants marked the extent of their current sense of discomfort by shifting the task bar on the scale on a tablet. The position of the marker has been converted to a value between 0 and 100. This query was performed for the following 15 body parts: neck, left and right shoulder, left and right arm, upper and lower back, left and right buttocks, left and right thigh, left and right knee, left and right calf. The values of the subjective assessment of the discomfort were entered by the participants at five different times - before the driving task started and after each one-hour driving section - via the discomfort query on the tablet. These values were imported into an Excel file and then entered into a SPSS file. The data of the subjectively experienced discomfort were in general on a low level. As a result, the data were nominally scaled: Each discomfort statement was clearly assigned to either the category *discomfort* or the category *no discomfort*. As soon as the VAS values were greater than zero, the discomfort statements were categorized to the category *discomfort*. Furthermore, discomfort statements were aggregated across all measurement times and body regions. In this way, the number of discomfort statements could be determined and compared between the conditions.

2.6. Muscle Stiffness

Stiffness of the lumbar and thoracic back muscle were measured with the *IndentoPRO* developed by the Fascia Research Group of Ulm University and the Professorship of Human Locomotion of Chemnitz University. This indentometer device has been used in several studies and is considered a valid and reliable instrument to measure muscle stiffness (Kett et al. 2021; Wilke et al. 2018). Following Kett and Sichtung (2020), two locations were chosen to measure the stiffness of the back muscles (Fig. 4): the thoracic spine musculature (around the fourth to sixth thoracic vertebra) and the lumbar spine musculature (around the first to third lumbar vertebra). The stiffness was measured 2 cm lateral to the spine (right side). To evaluate the muscle resistance against deformation, the plunger of the indentometer was pressed into the tissue with a defined indentation depth three times. The measurement depth for the muscle alongside the lumbar spine was set to 12 mm. For the muscle alongside the thoracic spine the depth was set to 8 mm, since the muscle is located more superficial (Kett and Sichtung 2020). Muscle stiffness of the participants was measured immediately before and after the sitting duration while they were lying in a prone position.

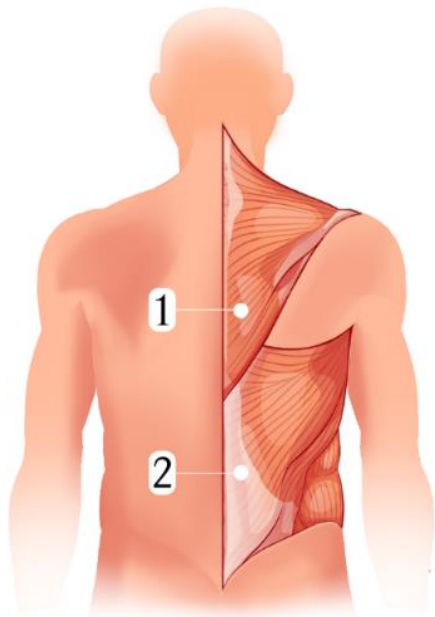


Figure 4: Locations of the muscle stiffness measurement.

For the pre-processing of the muscle stiffness data, the average differences between the pre- and post-measurements were calculated by subtracting pre- from post-measurements; thus, positive differences corresponding to an increase and negative ones to a decrease in muscle stiffness.

2.7. Statistical Analysis

The statistical analyses were carried out using *SPSS Statistics* (SPSS Statistics Version 24; IBM Corporation, USA). First, all variables generated in the data pre-processing were checked for the presence of the normal distribution using the Kolmogorov-Smirnov test. Due to the violation of the normal distribution in the motion score data, the hypothesis for significant differences between the test conditions was tested using a paired Wilcoxon signed-rank test. For the whole-body movement hypothesis a paired t-test was run. Due to the violation of the normal distribution in the muscle stiffness data, paired Wilcoxon signed-rank tests were used to compare the muscle stiffness before and after the 4.5-hour sitting period and to compare the differences in muscle stiffness chances between the conditions. For the discomfort data, the occurrence frequency of perceived discomfort, regardless of the strength of the discomfort, was used to investigate the discomfort hypothesis. The assumption of the normal distribution for the data was violated. A parametric method was therefore omitted and a chi-squared-test was calculated. The α -level was set to .05 for all statistical tests.

3. Results

One whole-body movement data set and three muscle stiffness data sets were removed due to recording problems. Accordingly, 16 data sets were taken into account for the evaluation of the motion score and the subjective experienced discomfort, 15 for the number of whole-body movements and 13 for the muscle stiffness.

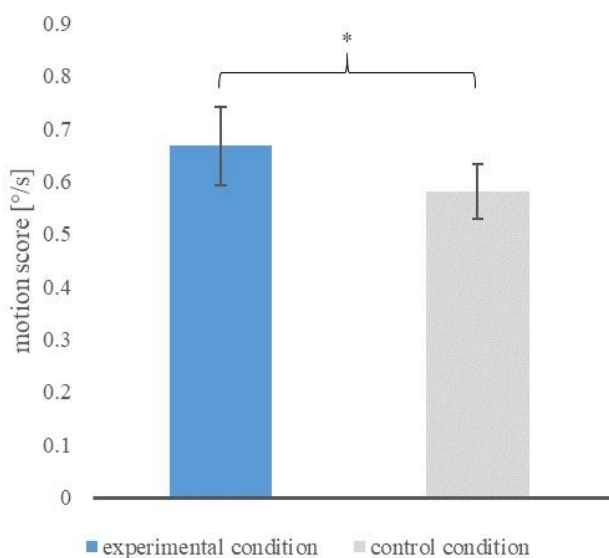


Figure 5: Average motion score while 4.5 hours driving depending on the test condition ($n = 16$). The error bars represent the standard error of the mean values. $*p < .05$.

The average motion score during the simulated 4.5-hour drive is shown in Fig. 5. The motion score was higher in the mobilization condition ($M = 0.67$; $SD = 0.07$) than in the control condition ($M = 0.58$; $SD = 0.05$). A Wilcoxon signed-rank test indicated that this difference was statistically significant, $n = 16$, $z = -2.38$, $p = .017$, $r = 60$.

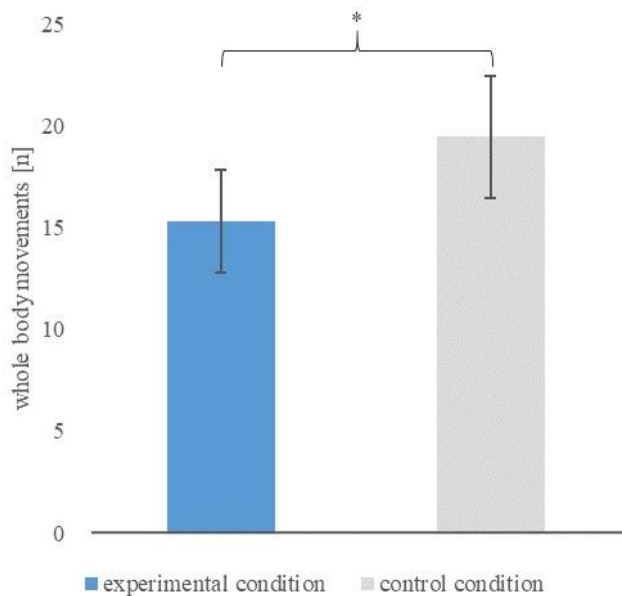


Figure 6: Average number of whole-body movements while 4.5 hours driving depending on the test condition ($n = 15$). The error bars represent the standard error of the mean values. $*p < .05$.

The average number of whole-body movements during the simulated 4.5-hour drive are shown in Fig. 6. Whole-body movements were significantly lower in the mobilization condition ($M = 15.33$; $SD = 10.81$) than in the control condition ($M = 19.47$; $SD = 12.06$), $t(14) = 2.25$, $p = .041$, $d = 0.55$.

Six out of sixteen participants reported subjective discomfort during the test in both the experimental and control condition. Ten participants did not feel any discomfort at any time in either the mobilization or the control condition. Perceived discomfort was stated 47 times in the experimental condition and 76 times in the control condition, respectively. These numbers were compared between the conditions using a chi-squared test. It showed a significant difference between the observed and expected frequencies of discomfort, $\chi^2(1) = 7.21$, $p = .007$, $\phi = 0.06$. Therefore, a feeling of discomfort was more likely to occur in the control than in the experimental condition.

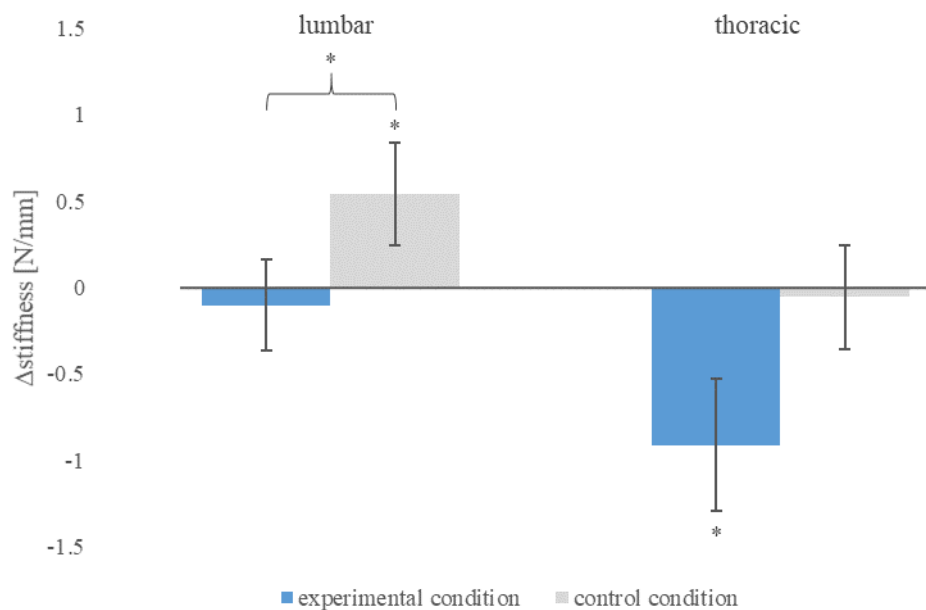


Figure 7: Average difference of the lumbar and thoracic muscle stiffness values before and after 4.5 hours driving depending on the test condition ($n = 13$). The error bars represent the standard error of the mean values. $*p < .05$.

The average difference of the lumbar muscle stiffness values before and after the 4.5-hour driving task depending on the test condition is shown in Fig. 7. In the control condition the stiffness values were on average higher after the driving task ($M_{\text{Post}} = 5.10$, $SD_{\text{Post}} = 0.99$), than before the driving task ($M_{\text{Prä}} = 4.56$, $SD_{\text{Prä}} = 0.95$). A Wilcoxon signed-rank test indicated that this increase was statistically significant, $n = 13$, $z = -2.27$, $p = .023$, $r = .63$. In contrast, the stiffness values remained on almost the same level in the mobilization condition ($M_{\text{Prä}} = 4.51$, $SD_{\text{Prä}} = 0.92$, $M_{\text{Post}} = 4.41$, $SD_{\text{Post}} = 0.99$). The change in muscle stiffness over time differs significantly between the mobilization ($M = -0.10$, $SD = 1.00$) and the control condition ($M = 0.54$, $SD = 0.84$); Wilcoxon signed-rank test: $n = 13$, $z = -2.13$, $p = .033$, $r = .59$.

The average difference of the thoracic muscle stiffness values before and after the 4.5-hour driving task depending on the test condition is shown in Fig. 7. The thoracic muscle stiffness in the mobilization condition is significantly lower after the driving task ($M_{\text{Post}} = 6.04$, $SD_{\text{Post}} = 1.77$) than before the driving task ($M_{\text{Prä}} = 6.95$, $SD_{\text{Prä}} = 1.61$); Wilcoxon signed-rank test: $n = 13$, $z = -2.06$, $p = .039$, $r = .057$. In the control condition muscle stiffness remained almost steady ($M_{\text{Prä}} = 6.74$, $SD_{\text{Prä}} = 6.69$, $M_{\text{Post}} = 6.74$, $SD_{\text{Post}} = 2.41$). There is no significant difference in the change in muscle stiffness over time between the mobilization condition ($M = -0.92$, $SD = 1.43$) and the control condition ($M = -0.06$, $SD = 1.03$); Wilcoxon signed-rank test: $n = 13$, $z = -1.50$, $p = .133$.

4. Discussion

The present study tested the effects of the *Mobilization Seat* on motion activity, muscle stiffness and discomfort of long-haul truck drivers during a 4.5-hour drive in a driving simulator under monotonous highway conditions. In accordance with the hypothesis, there is a significant difference in motion activity between the conditions. The average motion score in the mobilization condition was significantly higher than in the control condition. This result is conform to the findings of a laboratory study conducted in 2020 which showed that mobilization promotes postural movements. In 10 participants, an average rotation of the thoracic spine area of 1.3° was detected (Daimler AG 2020). These measured micromovements may accumulate over the 4.5-hour drive, which could explain the higher values of the motion score in the mobilization condition. Positive effects of these small rotational movements of the spine can be assumed, since low-frequent pressure changes in the intervertebral disc can improve their nutrition (Pellettiere et al. 2006; van Deursen et al. 2000). Due to the sustained compression on the intervertebral disc while sitting, disc nutrition is affected adversely (Maroudas et al. 1975) caused by a restrained fluid flow into the disc (Kingma et al. 2000). The inflating and deflating air cushions move different body segments dynamically in different directions and therefore promote dynamic sitting. Dynamic sitting could provide beneficial physiological effects such as reduction of spinal shrinkage (van Deursen et al. 2000), which is partly explained by fluid flow from the disc (Roberts et al. 1998) and preventing muscle fatigue (van Dieën et al. 2001).

The results show a hypothesis-confirming difference between the numbers of whole-body movements in the conditions: Drivers have moved their whole body more frequently in the control condition than in the mobilization condition. Following the literature, people compensate discomfort when moving unconsciously to relieve joint pressure (Hirao and Kitazaki 2006) and pressure of compressed body parts with impeded blood flow (Hermann and Bubb 2007 - 2007). It is therefore reasonable to assume, that the imposing micromovements due to the mobilization function could have the potential to relieve compressed body parts and to reduce discomfort during prolonged driving. This finding is partly reflected in the subjective discomfort values: The hypothesis that the participants perceived less discomfort in the experimental condition than in the control condition due to the mobilization function in the seat could be confirmed. Despite the long sitting period, it needs to be emphasized that the subjective discomfort was generally on a low level. Only six out of sixteen participants reported subjective discomfort during the test in both the mobilization and the control conditions. Previous research demonstrated that the driving duration influences the experienced discomfort of the participants. With a sitting period of 4.5 hours this study investigated a longer duration than other studies (Mansfield et al. 2014; Sammonds et al. 2017). Most studies showing a significant increase in discomfort while driving recruit people with a car driver's license (Mansfield et al. 2017; Varela et al. 2019), but not necessarily a truck driver's license. It is possible, that the sense of discomfort differs between professional and non-professional drivers. Giacomini and Screti (2005) have suggested, that

the factor *driving experience* could affect discomfort during a driving task: Non-professional drivers were found to provide higher discomfort responses than professional drivers. However, a study of Cardoso et al. (2019) showed the effectiveness of a newly developed seat on reducing the perceived discomfort of commercial licensed truck drivers.

Even though the subjectively experienced discomfort was on a small level, the objective method used in this study quantified discomfort indirectly. While subjective ratings are always momentary, a measurement technology could be used to detect whole-body movements continuously. As soon as repeated whole-body movements on long distance rides occur, an intervention, for example the *Mobilization Seat*, could be offered to the driver to reduce discomfort.

In line with Masaki et al. (2017), our study shows that discomfort can be affiliated with increased lumbar muscle stiffness. The results of Kett and Sichtung (2020), showing lumbar muscle stiffness increases significantly after a 4.5-hour sitting period, could be confirmed in the simulated driving context. The change in lumbar muscle stiffness over time differs significantly between the mobilization and the control condition. In the control condition, the stiffness values were significantly higher after the driving task than before. In contrast, the stiffness values remain on almost the same level with the application of the mobilization. Thus, an increase in lumbar muscle stiffness over a sitting period of 4.5 hours could be prevented by using the *Mobilization Seat*. In contrast to the lumbar area, thoracic muscle stiffness values did not increase significantly after the sitting period in the control condition and there was no significant difference in the change in muscle stiffness over time between the mobilization condition and the control condition. The steering task and the shape of the truck driver's seat may have led to a more upright sitting posture (Kim 2018) in comparison to the mostly preferred slumped sitting posture in the office, which affects trunk stiffness adversely (Hendershot et al. 2011; Kett et al. 2021). This may explain why thoracic muscle stiffness remained almost steady in the control condition. When interpreting these results, the difference in the baseline values of the muscle stiffness should also be noted: The pre-measured values in the thoracic spine of professional drivers were on average 2.44 times higher ($M = 6.85$, $SD = 1.77$) than the values of the participants recruited by Kett and Sichtung (2020) ($M = 2.80$, $SD = 0.83$). This may be explained by differences in age, activity level and sex of the participants (Eby et al. 2015). If the muscle stiffness could also be influenced by profession is actually not investigated. The higher level of the baseline values may have had effects on the changes in thoracic muscle stiffness in our study. In contrast to the nearly consistent values in the control condition, the mobilization function induces a significant reduction in muscle stiffness in the thoracic spine. Similar results were achieved with the foam roller device investigated in the study by Kett and Sichtung (2020). Both interventions apply pressure and friction on the underlying tissues alternately.

4.1. Limitations

In order to standardize the driving situation, the effects of the *Mobilization Seat* were investigated in a driving simulator, implying certain limitations: The unnatural laboratory conditions may have influenced the sitting behavior. The occurrence of a Hawthorne effect is also conceivable: Although the investigators monitored the experiment outside the participant's sight, they knew that they were being observed, which may have led to a change in natural behavior and there influenced the conducted measures. In addition, the tight full-body suit which participants had to wear for the measurement of motion activity, possibly restricted the natural movement behavior. In future studies, if possible, wearing the suit should be therefore avoided. Furthermore, there might be another sitting posture in a truck than in the built driving simulator since the steering wheel and the pedals did not correspond exactly to the actual conditions in the truck. Another noteworthy limitation of a static driving simulator is the missing whole-body vibrations while driving. Previous research has shown that they significantly affect the onset of discomfort (Mansfield et al. 2014; Du et al. 2018). A variety of extraneous factors could have influenced the participants' discomfort statements. The validity of subjective ratings depends on the ability of the participants to accurately describe their perceived discomfort (Hermann and Bubb 2007 - 2007). The relatively low values in the subjective discomfort query may be explained by the social desirability concerns of the interviewees. The participants might have tended to embellish their answers in order to give socially desirable answers, which naturally would have resulted in lower discomfort values. For this reason, we have also recorded the discomfort objectively. In addition, only male participants participated in the present study, which is why the generalizability to female drivers can be critically questioned. Due to the predominant share of men in the occupational group of professional drivers (98 %), however, this limitation is almost negligible for the generalizability to the target group.

4.2. Research Outlook

To ensure generalizability of the results, a replication of the study needs to be carried out in a real traffic surrounding. Furthermore, evaluations under dynamic long-term driving should be conducted in further studies. For a series application, we recommend linking the activation of the mobilization system with an embedded whole-body movement detection system. A seat-integrated sensor technology could be used to detect sitting behavior and offer to activate the *Mobilization Seat* as soon as repeated whole-body movements on long distance rides occur. Due to the increasing prevalence of sedentary jobs (van der Ploeg et al. 2015) a transfer of the mobilization function in office chairs is suggested.

5. Conclusion

Driver shortage is a relevant issue in the transport industry. Logistic companies must provide benefits to hire qualified and motivated employees and to be able to retain them long term. Working conditions are having an adverse impact on health risks of the drivers causing social and economic damage through illnesses and high sick leaves.

To make the profession more attractive and to promote drivers' health, the purpose of this study was to test the effects of the *Mobilization Seat* on the musculoskeletal system. Therefore, the study was conducted under using a strong experimental design (within participants, repeated measures). With gathering motion activity, muscle stiffness and discomfort the study included a wide range of variables to investigate the health-preventing potential of the seat. This study intended to investigate the mentioned parameters over a simulated 4.5-hour drive, which is equivalent to the maximum legal driving time (without a break) in Europe.

Altogether, the results suggest wholesome effects of the seat-integrated mobilization system whilst prolonged driving. The study indicates that the use of the *Mobilization Seat* contributes to increase health beneficial micromovements by activating air cushions in the backrest and in the seat pan. The motion activities were higher in the mobilization condition than in the control condition, whereas the whole-body movements of the participants were on a lower level. The study confirms, whole-body movements to be a potential physiological indicator for discomfort, which was reflected in the subjective measure: The participants experienced less discomfort in the mobilization condition. An increase of the muscle stiffness, which is often connected with LBP and discomfort, could also be prevented due to the mobilizing function.

As a final evaluation, it can be stated that the *Mobilization Seat* has the potential to counteract the effects of the sedentary behavior which long-haul truck drivers are exposed to and, moreover, could be an intervention to make the profession of a truck driver more attractive.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The study was supported by the Mercedes-Benz AG.

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5.2. Anpassung der Aktivität der Rückenmuskulatur bei Fernfahrenden während langer Fahrten mit und ohne sitzintegrierte Mobilisation

Adaptions in back muscle activity in long-haul truck drivers during prolonged driving with and without seat-integrated mobilization

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Abstract

Objective: The aim of this study was to investigate the development of back muscle activity during a simulated 4.5-h truck drive with professional long-haul truck drivers and to assess the effects of a seat-integrated stimulation on muscle activity during the drive.

Method: Muscle activity was compared intra-individually between a stimulation condition (with seat-integrated stimulation) and a no-stimulation condition (without seat-integrated stimulation) in a simulated driving study ($N = 16$). During the drive, sEMGs of the m. trapezius pars descendens, m. trapezius pars ascendens and m. erector spinae were recorded bilaterally and the RMS values of the sEMG amplitudes were analyzed.

Results: There was a significant increase in muscle activity within 1-h driving periods (in m. trapezius pars descendens and m. trapezius pars ascendens) in both the stimulation and the no-stimulation condition but not within the whole sitting duration (in all muscles). Contrary to our expectations, the RMS values did not differ between conditions.

Conclusion: Short-term effects on back muscle activity of long-haul truck drivers during 1-h driving periods were found with and without the seat-integrated stimulation. However, interruptions of the driving task seemed to be sufficient to eliminate these effects. These findings on back muscle activity in long-haul drivers reveal new insights as to what affects the musculoskeletal system in prolonged driving.

Outlook: In future studies, an uninterrupted driving task under real conditions should be used to investigate possible effects of prolonged driving on truck drivers' muscle activity in general and of seat-integrated stimulation on back muscle activity in particular.

1. Introduction

Professional driving implies excessive sedentary behavior due to long uninterrupted driving times. Several diseases involving the musculoskeletal system are associated with prolonged restricted postures and static muscle load to which truck drivers are exposed (Mozafari et al., 2015). This has immense health and economic impacts: Low back pain (LBP) is the leading factor causing work absenteeism in professional drivers (Hakim & Mohsen, 2017). The risk of LBP clearly increases if prolonged sitting is accompanied by the exposure of whole-body vibration and awkward positioning (Lis et al., 2007). However, several studies have shown that sitting for long periods of time with little postural variation, for example in the office, is also associated with LBP (Harrison et al., 1999; Mork & Westgaard, 2009). While truck driving the possibilities to change posture are even more limited compared to the office environment due to operating the steering wheel, pedals and the requirement to monitor the rear mirrors and the street (Gyi, 2013; van Veen & Vink, 2016).

The legally prescribed driving time of professional drivers in accordance with Regulation (EC) No 561/2006 of the European Parliament and of the Council of 15 March 2006 is 4.5 hours. During this time, back muscles are required to stabilize the driving posture (van Dieën et al., 2001). The low-level static load of the muscles may be a primary reason for musculoskeletal disorders. The low but prolonged muscle contractions cause reduced muscle oxygenation (McGill et al., 2000), stiffness (Kett & Sichtung, 2020), discomfort (El Falou et al., 2003) and pain (Mork & Westgaard, 2006; Saiklang et al., 2022; Schinkel-Ivy et al., 2013). Accordingly, the number of working hours is positively associated with the frequency of LBP in truck drivers (Andrusaitis et al., 2006).

To assess the role of low-level static muscle load in the development and occurrence of LBP, the adaptations of back muscle activity during prolonged low-level muscle load were investigated. Mork and Westgaard (2006) have shown a high risk of muscle pain in sustained low muscle activity of the upper trapezius muscle. An experiment by Ding et al. (2020) showed a significant correlation between the perceived discomfort and the muscle activity in office workers. They found an increase in back muscle activity and discomfort after 40 minutes of sedentary work. During a two-hour sitting period Schinkel-Ivy et al. (2013) found an increase in muscle activation which correlated significantly with pain development. Callaghan and McGill (2001) examined lumbar spine kinematics, spinal joint loads and trunk muscle activation during the same sitting periods. The continuous spinal loading with minimal

motions while sitting exhibited a shift to higher levels of back muscle activation. In automotive seating Kolich et al. (2001) measured an increase in muscle activity in a one-hour sitting period, which was interpreted to be related to the onset of muscle fatigue. An increase in EMG amplitude as a result of a four hour driving could also be found by Sheridan et al. (1991). For truck driving, similar results were found and interpreted as an effect of muscle fatigue by Katsis et al. (2004). Bartuzi and Tokarski (2010) investigated the influence of different body postures on muscle activity while sitting in a static truck seat for 30 minutes. It was not reported in any of these truck studies whether the participants were professional truck drivers or not. For one study the duration of driving was also not specified. Hence, the occupational group of professional truck drivers has not been the center of interest in many studies on muscle activity. Although given their risk profile, focusing on truck drivers seems to be of particular relevance. For instance, given that long sitting time constitutes a vast extend of long-haul truck drivers' everyday life, their sitting behavior may well differ from that of casual car drivers or of people who commute to work.

To quantify activity of the back muscles, surface electromyography (sEMG) is commonly used. Amplitude parameters of the signal measured by surface electrodes placed on the skin can be seen as indicators of muscle activity or muscle load whereas a change in amplitude may also indicate muscle fatigue (de Luca, 1997; Stutzig & Siebert, 2015). Moreover, fatigue-related changes in muscle activity affect the frequency spectrum of the electrical signal (Mohseni Bandpei et al., 2014). Specifically, with increasing muscle fatigue a higher muscle activity and therefore a higher number of action potentials is required, resulting in an increase in the EMG amplitude (Basmajian & de Luca, 1985; de Luca, 1997; Jia, 2021; Katsis et al., 2004). The increase of the sEMG amplitude during prolonged, low-level static contractions might be explained by "neurogenic changes" and/or a "decrease in action potential conduction velocity along the muscle fibers" (Jørgensen et al., 1988, p. 318). The shift of EMG amplitude parameters in the direction of higher amplitudes has been shown frequently for various muscles (Hammarskjöld & Harms-Ringdahl, 1992; Jørgensen et al., 1988; Katsis et al., 2004; Kleine et al., 2000; Kolich et al., 2001; Moritani et al., 1986). However, an increase in sEMG amplitudes could also indicate higher muscle activity due to body movements. Therefore, motion activity should also be recorded during sEMG measurements to enable an unambiguous interpretation of the sEMG data (Sheridan et al., 1991).

To interrupt static strain while prolonged sitting and therefore to reduce back muscle activity and LBP occurrence, various intervention strategies have been investigated, mainly in office or automotive contexts. For instance, dynamic backrests and seat pans as well as alternating rotations of the seat of a chair in the horizontal plane have been proposed to reduce LBP in prolonged sitting (van Deursen et al., 1999; van Dieën et al., 2001) compared to conventional chairs. Kolich et al. (2001) reported a decrease in EMG amplitude over time using two mechanical lumbar support systems in automobile

seating, indicating that these support systems might reduce the risk of LBP. In addition, Franz et al. (2011) reported a reduction in EMG amplitude as the result of using a pneumatic massage system in the backrest of a car seat. In a previous study (Schneider et al., 2023), we have shown that a stimulation system in a truck driver's seat significantly reduces drivers' discomfort as well as muscle stiffness during a 4.5-hour driving task. The seat used in this study includes air cushions in the backrest and seat pan which move segments of the body of the person sitting on the seat in different directions. So far, the effect of the new seat and its stimulation system on back muscle activity during a 4.5-hour driving task is unknown.

In the present study we investigated the surface EMG of back muscles during prolonged 4.5 hour driving in professional long-haul truck drivers. Additionally, we applied a stimulation assuming that the alternating, seat-integrated inflating cushions might interrupt static muscle strain while driving and therefore reduce back muscle activity. As a consequence, this contributes to the prevention of LBP. With regard of the current state of research, we expected an increase in sEMG amplitude of the back muscles over the 4.5-hour drive in a test condition without stimulation which is not simply the manifestation of body movements. In the test condition with stimulation, in contrast, we expected a lower increase in sEMG amplitude than in the condition without stimulation.

2. Material and Methods

2.1. Participants

Fifteen male professional truck drivers (age: $M = 42$ years, range: 24 to 57 years; weight: $M = 90$ kg, range: 75 to 108 kg; height: $M = 180$ cm, range: 172 to 192 cm; body mass index: $M = 28$ kg/m², range: 23 to 32 kg/m²) participated in two simulated driving sessions for two consecutive days. The truck drivers' average driving distance was approximately 64,700 km (40,200 miles) per year. A requirement for participating was a sitting duration of at least 4.5 hours per day. Participants with a body mass index higher than 35 kg/m² were excluded because electrical conductivity varies among other things with tissue thickness (Konrad, 2006). Since only 2 % of all truck drivers globally are women (International Road Transport Union, 2021), only men were recruited to participate in the present study. All participants were informed about the aims and risks of the experiment and gave their written consent. The study was approved by the ethics committee of Daimler AG and conducted according to the latest declaration of Helsinki.

2.2. Experimental Design, Materials and Procedure

To standardize the driving situation, the experiment was conducted in a driving simulator. All participants performed a simulated driving task in two test conditions on two different days. In the stimulation condition participants performed the driving task using the seat-integrated stimulation (see below) with the stimulating system turned on. In no-stimulation condition, the stimulation system was turned off and participants were told that they would be exposed to olfactory stimulation; this was done in an attempt to equate the two test conditions and to minimize possible effects of social desirability.

The sequence of the test conditions was randomized for every participant. In addition to the sEMG, motion activity was measured using a motion capture system by Xsens Technologies B.V., Netherlands. This was done to control for muscle activity due to body movements. Participants arrived at the lab at 8:30 a.m. on both survey days. The preparation phase (SARS-CoV-2 test, demographic questionnaire, attachment and calibration of the measurement instruments) took about three hours. The sitting duration during the simulated drive was 4.5 hours. The subsequent follow-up period in which the measurement instruments were removed took about half an hour. This resulted in a total study duration of eight hours per day, that is, 16 hours for the entire two-day study for every participant.



Figure 8: The experimental set-up including the static truck driving simulator.

The driving simulator used in the present study was a static truck driving simulator with an automatic gearshift (Figure 9). The seat-integrated stimulation had been developed in the research department of Daimler AG and its function has been published by *Deutsches Patent- und Markenamt* (German Patent and Trade Mark Office) under the reference number DE 10 2018 000 765 A1. The seat-integrated stimulation consists of four different stimulation sequences during which air cushions are inflated and deflated in the backrest and seat pan. Logitech's *G29* steering wheel and pedal unit (model number 941-000112) featured a 900-degree steering angle, force feedback and a nonlinear brake pedal. The steering wheel differed in diameter from a truck steering wheel but had all functions that were necessary for the driving task. The *Euro Truck Simulator 2* simulation software, developed by SCS Software and installed on a separate computer, was used for the truck driving simulation. During the driving task, the simulated road and its immediate environment were displayed on a SHARP 55BJ3E 4K Ultra HD Smart LED TV (model number 4T-C55BJ3EF2NB) with a diagonal length of 139.7 cm. The monitor was placed at a distance of about 180 cm in the direct field of view in front of the participant.

At the beginning of the simulated driving task, the participants were familiarized with the truck driving simulator. They were encouraged to adjust the seat and steering wheel positions according to their needs. Following this, the first of four one-hour driving periods started. For every period the driving task was identical: a monotonous tour on a motorway. A primarily straight motorway was chosen in order to avoid movements due to stops, curves and shunting processes. After each one-hour driving period there was a six-minute break which was necessary to save the measurement records (our technical equipment did not allow for longer measurement periods). Still sitting, the participants were able to drink and eat something during the breaks. After the 4.5-hour sitting period the measurement equipment was removed and an acceptance questionnaire was filled out.

2.3. Electromyography

To quantify back muscle activity during the prolonged monotonous driving task sEMG was used. Data were collected by an *MP160* system (Biopac Systems Inc., USA). The 16-channel system included the *AcqKnowledge* software version 5.0.2 (Biopac Systems Inc., USA) with various analysis functions. The Dual Wireless EMG *BioNomadix Pair* (Biopac Systems Inc., USA), consisting of a transmitter and receiver module, enabled the wireless recording of signals with a Common Mode Rejection Ratio of at least 90 dB and a differential input impedance of 2 M Ω . Using the Biopac module, raw sEMG signals were collected at 2,000 Hz, pre-amplified at 2,000 gain, and band-pass filtered with cut off frequencies of 10 and 500 Hz, respectively.

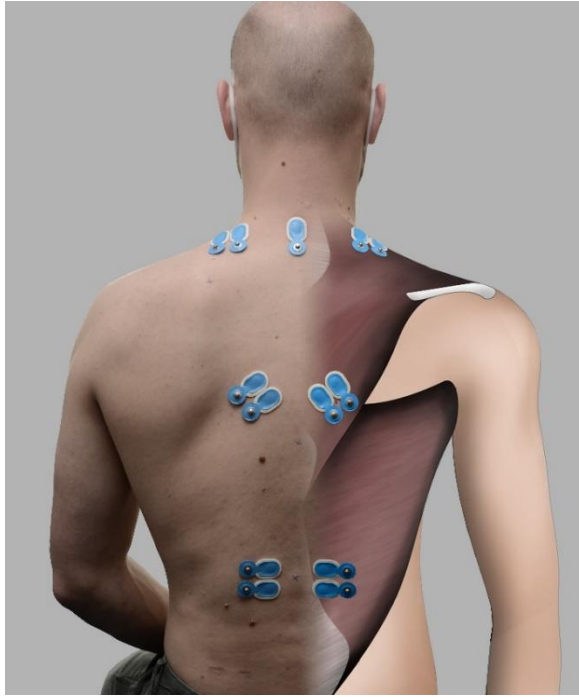


Figure 9: Position of the surface electrodes.

The electrodes were placed at three back muscles bilaterally (2): m. trapezius pars descendens, m. trapezius pars ascendens and lumbar m. erector spinae. The placement of the electrodes followed the SENIAM recommendations for sEMG data collection (Hermens et al., 2000). In addition, the findings of Barbero et al. (2012), who had identified the innervation zone of a muscle as the most unfavorable place for the placement of a pair of electrodes, were taken into account. For the placement of the electrodes on the m. trapezius pars descendens we first palpated the C7 and the acromion on the right and left body. According to the SENIAM guidelines, the electrodes are to be placed midway on the line between acromion and C7, but due to the consideration of the innervation zones, the pair was placed 1.5 cm medial from this point. For the placement of the electrodes on the m. trapezius pars ascendens, the eighth thoracic vertebrae (Th8) and the trigonum spinae scapulae were first localized as anatomic landmarks. At two-thirds of the linear distance from the trigonum spinae scapulae to the Th8, the electrodes were placed in the direction of the muscle fibers. The electrodes on the lumbar erector spinae muscle group were placed two centimeters laterally of the first lumbar vertebrae on each side of the spine.

Bipolar Ag/AgCl (*BlueSensor N-00-S*, Ambu Inc, Colombia, size: 22 × 30 mm) surface electrodes were placed at points parallel to the muscle tissue with an interelectrode distance of 20 mm on the muscle bellies. A reference electrode was placed on C7 spinous process. Before applying the electrodes, the skin was shaved, roughened with a special peeling and cleaned with alcohol. For best-performing biopotential measurements, impedance was tested before trials using the *BIOPAC EL-CHECK* (Biopac

Systems Inc., USA). If the impedance exceeded 10 kΩ, the electrodes were removed and replaced until the impedance was lower than 10 kΩ.

Preliminary data had shown that the sEMG signals may be contaminated by electrocardiogram (ECG) signals. To eliminate those ECG contaminations, the ECG signal was measured by bipolar derivation using an additional module of Biopac (Trappe & Schuster, 2020). In a first step, the maximal amplitudes of the R waves (*r* peaks) in the QRS complex of the ECG signal were identified. In a second step, a time window of 160 ms was defined around the *r* peaks. These time windows were used to identify the ECG contaminations in the sEMG signal. In a third step, the raw sEMG signal was filtered using a 50 Hz 4th order low pass Butterworth filter. The filtered sEMG signal was subtracted from the raw sEMG signal only within the 160-ms time windows (Nougarou et al., 2018). In this way, the ECG artifacts could be eliminated from the raw sEMG signal without changing the raw signal too much.

Similar to Kolich et al. (2000), changes in sEMG amplitude in the form of the root mean square (RMS) were used in order to quantify muscle activity. Based on Konrad (2006), the RMS of the sEMG was calculated using a 500-milliseconds sliding window. In the stimulation condition, sEMG data were only collected in, and RMS values were only calculated for, time segments in which the stimulation system was off. This was done to avoid noise in the data, as in the approach of Kolich et al. (2000). The pressure exerted by the air cushions on the electrodes might have led to an increase in amplitude in the sEMG signal (van Dieën et al., 2001) during the stimulation phase. Consequently, RMS was calculated for 12 segments of 45 seconds each. The average RMS of these 12 segments represented the muscle activity in a one-hour driving period. The RMS values averaged over 15-minute sub-sections (each consisting of three successive segments) were used to observe the development of the sEMG amplitude within the one-hour driving periods in more detail. This classification of segments (shown in Figure 3) was also adopted for the no-stimulation condition to ensure comparability.

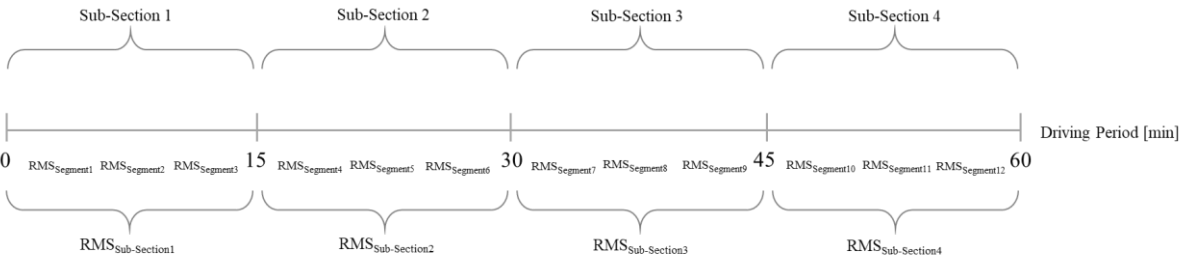


Figure 10: Division of one driving period into four sub-sections with 3 segments each (12 in total) for the calculation of the RMS values.

Prior to the sEMG data collection while driving, resting sEMG measurements were taken in a prone position for one minute. The RMS value calculated from these resting measurements was used to

differentiate signal contents in a sitting position from noise in a relaxed position without arbitrary muscle contraction.

All sEMG amplitudes were then normalized to a reference value. To obtain a reference value, isometric *maximal voluntary contraction* (MVC) exercises were performed for all three muscle groups: The MVC exercises for the m. trapezius descendens were isometric lateral raises at 100° shoulder abduction against fixed chains based on Al-Qaisi and Aghazadeh (2015). Instead of working with fixed chains, weights were used in the present study. The weights were adjusted individually to the strength of each participant. The maximum weight for a triple repetition of the exercise was chosen. For the MVC of the m. trapezius ascendens a prone lying shoulder external rotation and horizontal extension with the arm positioned at 90° of abduction with individually adapted weights was chosen (Ekstrom et al., 2003; McCabe et al., 2007). For the MVC of the m. erector spinae, the elbows were bent and the back of the hands were placed on the forehead in a prone position. One investigator exerted external resistance on the shoulder blades of the participants while the other investigator locked the participants' legs into position. The participants were then asked to raise and hold their upper limb against the external force (Konrad, 2006; Szpala et al., 2011). As suggested by Konrad (2006), the participants were asked to increase the force in the particular exercise to the maximum within 3 to 5 seconds, to maintain the force for the same period of time and then to relax within 3 to 5 seconds. This cycle was repeated three times with a 30-second break in between. The MVC exercises had been tested for feasibility in a preliminary pilot study.

To calculate the sEMG amplitude relative to MVC (%MVC), the mean RMS values were then divided by the mean RMS value obtained during the MVC exercises for each muscle. Following Kolich et al. (2000) the values were averaged across bilateral muscles.

2.4. Motion Analysis

In order to test relations between muscle activity and motion activity, the participants' movements were recorded using a full-body human motion capture system produced by Xsens Technologies B.V., Netherland. The system consists of a full-body *MVN Link* suit with 17 wired inertial and magnetic trackers. The software package *MVN Analyze 2019.2* was used to calculate positions and orientations of individual body parts as well as the angles of joints based on a biomechanical model of the human body. Accuracy of these measures have been validated by Schepers et al. (2018).

To quantify motion activity, we focused on three joint angles which we assume to describe the participants' seat fidgets and movements best while driving (Tatsuno & Maeda, 2019): the angle

between the trunk and a virtual vertical axis and the angles between the pelvis and both upper legs. Similar to Schneider et al. (2023) we calculated a so-called *motion timeline* which we defined as the sum of the absolute values of the changes in all angles at each time point. The mean value of the motion timeline was calculated within the RMS segments as defined above. Thus, motion was only measured within the segments in which the sEMG was recorded, resulting in a so-called *motion score* for each segment. The data processing was performed using *Matlab* (R2020b, The MathWorks Inc., USA).

2.5. Statistical Analysis

The statistical analyses were carried out using *SPSS Statistics* (SPSS Statistics Version 24; IBM Corporation®, USA). First, all variables generated in the data pre-processing were checked for violations of the normal distribution assumption using the Kolmogorov-Smirnov test.

The sEMG amplitudes hypothesis was tested using the multivariate analysis of variance (MANOVA) approach to repeated-measures analyses (O'Brien & Kaiser, 1985). In our application, all multivariate test criteria correspond to the same exact F statistic which is reported. Partial eta square (η_p^2) is reported as a sample effect size measure. The within-participant independent variables were test condition (stimulation condition vs. no-stimulation condition), driving period (1 to 4) and sub-section (1 to 4). Separate repeated-measures MANOVAs were calculated for each of the three muscle groups. The sEMG amplitudes relative to MVC (%MVC) were compared between the resting measurement and the 4.5-hour drive (driving periods and sub-sections) using a paired Wilcoxon signed-rank tests. Due to the violation of the normal distribution in the motion score data, Spearman's rank correlation coefficient was used to evaluate the strength of the link between the motion score ($^\circ/\text{sec}$) and the sEMG amplitude relative to MVC (%MVC) during one-hour driving period (sub-sections 1 to 4) and during the whole simulated drive (driving periods 1 to 4). The level of α was set to .05 for all analyses reported in this article.

3. Results

One sEMG data set and three kinematic data sets were unusable due to recording problems. Accordingly, 14 data sets for sEMG amplitude relative to MVC (%MVC) and 13 data sets for motion score evaluation ($^{\circ}$ /sec) were included in the analyses.

3.1. Electromyography

Figures 4, 5 and 6 show the average sEMG amplitude relative to the MVC (%MVC) for the four one-hour driving periods (left side) and the four 15-minute sub-sections (averaged across driving periods, right side) as a function of the test condition (stimulation, no-stimulation) for m. trapezius pars descendens, m. trapezius pars ascendens and m. erector spinae, respectively. In addition, the sEMG amplitude relative to the MVC (%MVC) in the resting measurement is shown.

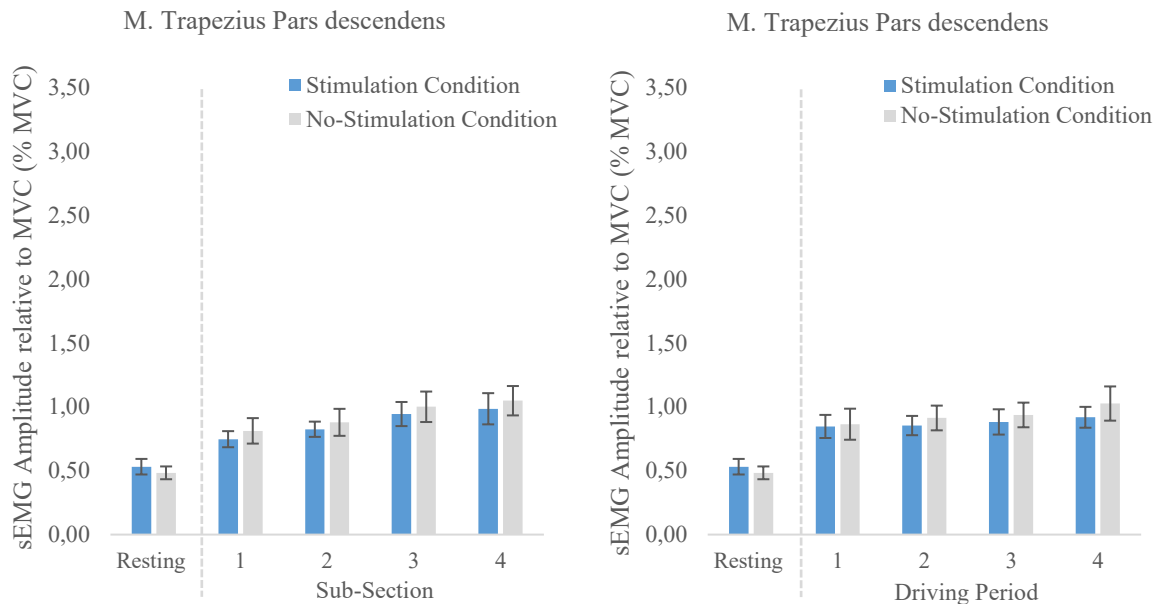


Figure 11: Average sEMG amplitude relative to MVC (%MVC) for m. trapezius pars descendens in resting measurement, over four 15-minute sub-sections (left) and over four one-hour driving periods (right) as a function of the levels of the test condition ($n = 14$). The error bars represent the standard errors of the mean values.

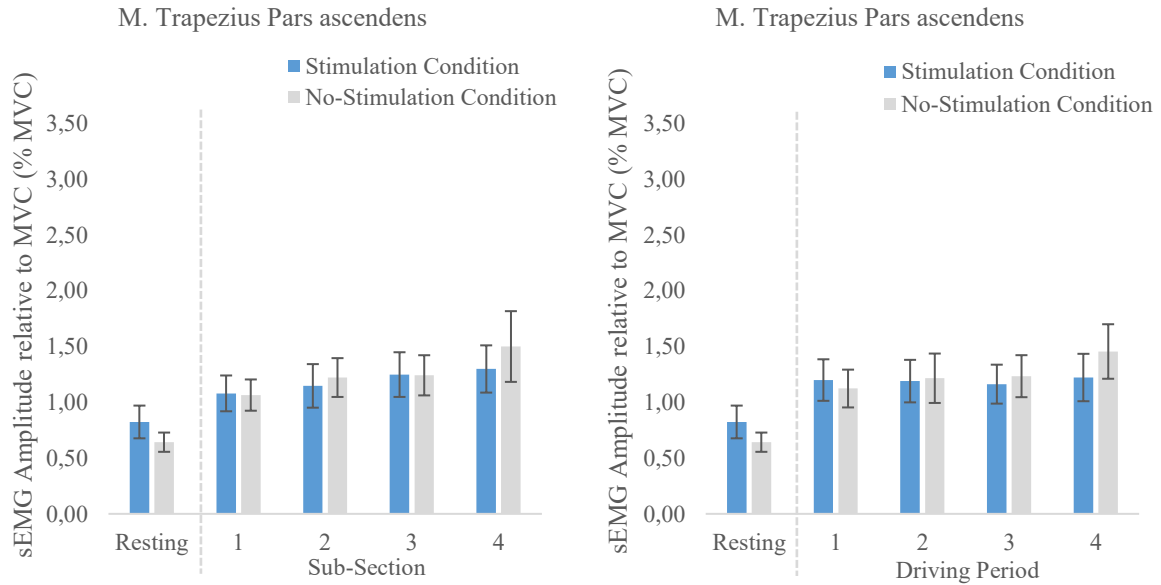


Figure 12: Average sEMG amplitude relative to MVC (%MVC) for *m. trapezius pars ascendens* in resting measurement, over four 15-minute sub-sections (left) and over four one-hour driving periods (right) as a function of the levels of the test condition ($n = 14$). The error bars represent the standard errors of the mean values.

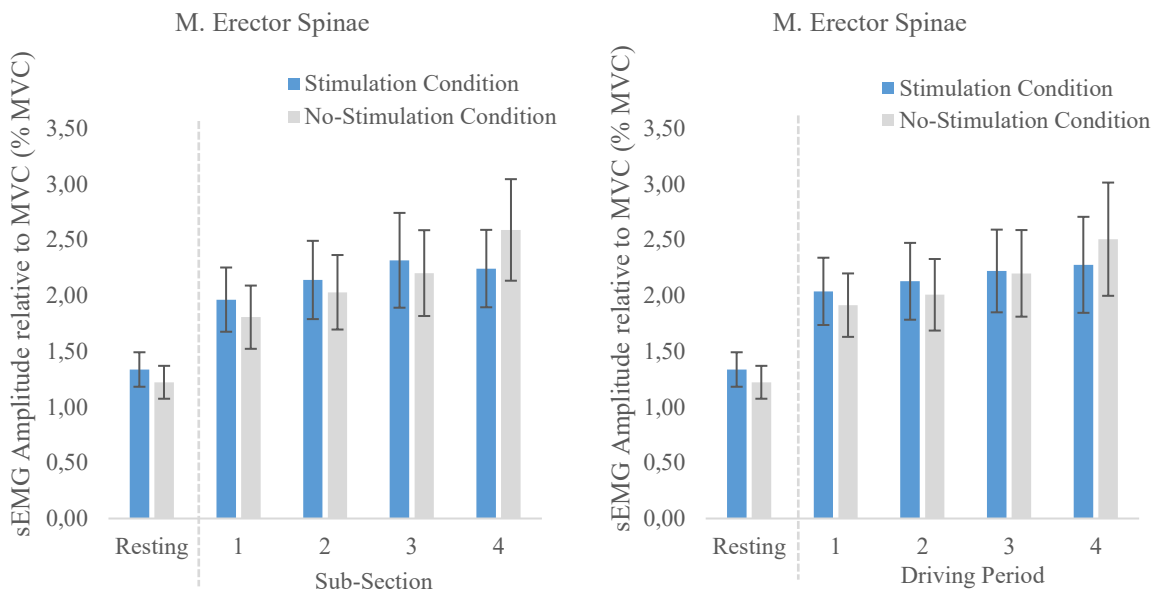


Figure 13: Average sEMG amplitude relative to MVC (%MVC) for *m. erector spinae* in resting measurement, over four 15-minute sub-sections (left) and over four one-hour driving periods (right) as a function of the levels of the test condition ($n = 14$). The error bars represent the standard errors of the mean values.

In order to test whether the sEMG amplitudes relative to MVC (%MVC) during the driving task differed from the resting measurement, a paired Wilcoxon signed-rank tests was used. The results showed that the sEMG amplitude in the resting measurement and the sEMG amplitude in the four driving periods and the sub-sections differed significantly for *m. trapezius descendens* in both the stimulation and the

no-stimulation condition, all $z > 2.17$, $p < .030$, for m. trapezius ascendens in the no-stimulation condition, $z > 2.42$, $p < .016$, but not in the stimulation condition, all $z < 1.85$, $p > .064$, and for m. erector spinae in both the stimulation and the no-stimulation condition, all $z > 2.29$, $p < .022$. This indicates a higher myoelectric activity in both driving conditions compared to the resting state.

Table 1: Results of 2 (stimulation vs. no-stimulation) \times 4 (driving period) \times 4 (sub-section) MANOVAs for each muscle group ($n = 14$). Statistically significant effects are typeset in bold.

Muscle	Effect	F-value	df (numerator)	df (denominator)	p-value	η^2
M. Trapezius Pars Descendens	Test Condition	0.426	1	13	.525	.03
	Driving Period	1.125	3	11	.381	.24
	Sub-Section	8.277	3	11	.004	.69
	Test Condition by Driving Period	0.362	3	11	.781	.09
	Test Condition by Sub-Section	0.012	3	11	.998	< .01
	Driving Period by Sub-Section	2.595	9	5	.153	.82
	Test Condition, Driving Period by Sub-Section	1.032	9	5	.515	.65
M. Trapezius Pars Ascendens	Test Condition	0.196	1	13	.665	.02
	Driving Period	1.282	3	11	.329	.26
	Sub-Section	3.773	3	11	.044	.51
	Test Condition by Driving Period	1.267	3	11	.333	.26
	Test Condition by Sub-Section	0.814	3	11	.512	.18
	Driving Period by Sub-Section	1.388	9	5	.375	.71
	Test Condition, Driving Period by Sub-Section	0.627	9	5	.744	.53
M. Erector Spinae	Test Condition	0.004	1	13	.948	.00
	Driving Period	0.773	3	11	.533	.17
	Sub-Section	3.424	3	11	.056	.48
	Test Condition by Driving Period	0.299	3	11	.825	.08
	Test Condition by Sub-Section	2.049	3	11	.165	.36
	Driving Period by Sub-Section	5.867	9	5	.033	.91
	Test Condition, Driving Period by Sub-Section	1.560	9	5	.325	.74

To investigate the development of sEMG amplitudes relative to MVC (%MVC) during the whole 4.5-hour truck drive and within the one-hour driving periods and to assess the effects of a seat-integrated stimulation sEMG amplitudes relative to MVC (%MVC) a repeated-measures MANOVA was calculated for each muscle group. The sEMG amplitude results of the 2 (stimulation vs. no-stimulation) × 4 (driving period) × 4 (sub-section) repeated-measures MANOVAs for each muscle group are shown in Table 1. The results are rather clear. Largely consistent effects are revealed for the sub-section variables which were statistically significant for m. trapezius pars descendens and m. trapezius pars ascendens and just missed the preset criterion for statistical significance for m. erector spinae. Additionally, a statistically significant effect was found for the driving period by sub-section interaction of m. erector spinae. This interaction was due to the fact that the sEMG amplitude in sub-section 3 of driving period 2 decreased. In all other sub-sections a continuous increase over the four driving periods occurred.

3.2. Motion Analysis

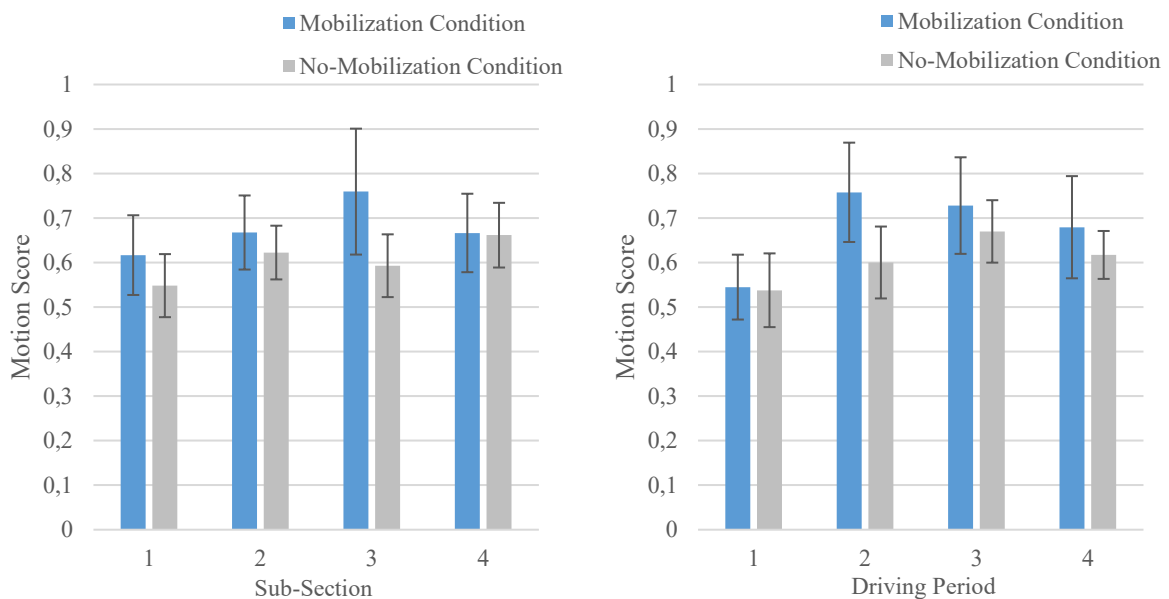


Figure 14: Average motion score over the four 15-minute sub-sections (left) and over the four one-hour driving periods (right) as a function of the levels of the test condition ($n = 13$). The error bars represent the standard errors of the mean values.

Spearman's rank correlation coefficient was used to evaluate the magnitude of the relationship between the motion score ($^{\circ}/\text{sec}$) and the sEMG amplitude relative to MVC (%MVC) during one-hour driving period (sub-sections 1 to 4) and during the whole simulated drive (driving periods 1 to 4). The average motion scores for both the stimulation and the no-stimulation conditions are shown in Figure 7. Spearman's rank-order correlations were calculated between the average motion score ($^{\circ}/\text{sec}$) and the

sEMG amplitude relative to MVC (%MVC) for each driving period and for each sub-section. As shown in Table 2, there was only one statistically significant correlation. This is even slightly less than what would be expected by chance given $\alpha = .05$. It thus seems possible to conclude that the average motion scores and the sEMG amplitude measurements do not correlate and that, as a consequence, the interpretation of the sEMG data is not complicated by possible motion effects.

Table 2: Spearman's rank-order correlations between the sEMG amplitude and the motions score in the driving periods and sub-sections. Statistically significant correlations are typeset in bold.

		<i>M. Trapezius Pars Descendens</i>		<i>M. Trapezius Pars Ascendens</i>		<i>M. Erector Spinae</i>	
Stimulation Condition	Driving Period 1	$\rho = -.03$	$\rho = .915$	$\rho = -.17$	$\rho = .590$	$\rho = .24$	$\rho = .426$
	Driving Period 2	$\rho = -.15$	$\rho = .629$	$\rho = -.08$	$\rho = .803$	$\rho = -.06$	$\rho = .845$
	Driving Period 3	$\rho = -.23$	$\rho = .448$	$\rho = -.18$	$\rho = .566$	$\rho = .16$	$\rho = .603$
	Driving Period 4	$\rho = -.52$	$\rho = .071$	$\rho = -.21$	$\rho = .482$	$\rho = -.13$	$\rho = .681$
	Sub-Section 1	$\rho = -.27$	$\rho = .374$	$\rho = -.18$	$\rho = .553$	$\rho = -.06$	$\rho = .845$
	Sub-Section 2	$\rho = -.52$	$\rho = .071$	$\rho = -.27$	$\rho = .374$	$\rho = -.30$	$\rho = .316$
	Sub-Section 3	$\rho = -.35$	$\rho = .239$	$\rho = -.06$	$\rho = .859$	$\rho = .02$	$\rho = .943$
	Sub-Section 4	$\rho = -.31$	$\rho = .306$	$\rho = -.31$	$\rho = .306$	$\rho = -.02$	$\rho = .945$
No-Stimulation Condition	Driving Period 1	$\rho = -.36$	$\rho = .231$	$\rho = -.21$	$\rho = .482$	$\rho = .32$	$\rho = .289$
	Driving Period 2	$\rho = -.17$	$\rho = .578$	$\rho = -.54$	$\rho = .055$	$\rho = .06$	$\rho = .845$
	Driving Period 3	$\rho = -.18$	$\rho = .553$	$\rho = -.12$	$\rho = .707$	$\rho = -.13$	$\rho = .668$
	Driving Period 4	$\rho = -.14$	$\rho = .655$	$\rho = -.42$	$\rho = .156$	$\rho = .39$	$\rho = .194$
	Sub-Section 1	$\rho = -.57$	$\rho = .044$	$\rho = -.49$	$\rho = .090$	$\rho = .06$	$\rho = .859$
	Sub-Section 2	$\rho = .00$	$\rho = 1.000$	$\rho = -.37$	$\rho = .216$	$\rho = .01$	$\rho = .972$
	Sub-Section 3	$\rho = -.28$	$\rho = .354$	$\rho = -.15$	$\rho = .629$	$\rho = .25$	$\rho = .405$
	Sub-Section 4	$\rho = -.26$	$\rho = .394$	$\rho = -.22$	$\rho = .471$	$\rho = .27$	$\rho = .374$

4. Discussion

The aim of this study was a) to investigate the development of back muscle activity during a simulated 4.5-hour truck drive in professional long-haul truck drivers and b) to assess the effects of a seat-integrated stimulation on the back muscle activity during the test drive. The index of muscle activity used here was the sEMG amplitude relative to MVC (%MVC). In defined RMS segments sEMG amplitudes

of three relevant muscles, the m. trapezius pars descendens, the m. trapezius pars ascendens and the m. erector spinae, were recorded bilaterally.

Based on results reported in the literature, we expected the low-level static muscle load in prolonged truck driving to lead to an increase in sEMG amplitude due to an increase in muscle activity over time (Bartuzi & Tokarski, 2010; Callaghan & McGill, 2001; Katsis et al., 2004; Schinkel-Ivy et al., 2013). Contrary to our assumptions, no significant increase in sEMG amplitude and thus no increase in back muscle activity was observed from the first to the fourth one-hour driving period. However, an increase in muscle activity was observed within the one-hour driving periods, showing that the sEMG measurements were sensitive to experimental manipulations. Due to the additional analysis of the motion score, the increase in sEMG amplitude as a manifestation of body movements, which typically occur during prolonged sitting (Sheridan et al., 1991), could be excluded. Despite the relatively low values of average muscle activity while driving (0.8 % of MVC in m. trapezius pars descendens and up to 2.5 % of MVC in lumbar erector spinae), sEMG amplitude during simulated driving mainly differed from the sEMG amplitude in the resting measurement. Consequently, it is possible to conclude that an activation of all investigated muscles is needed to maintain the sitting position. In the experiment reported here, this resulted in static low-level load of the back muscles which has led to an increase in EMG amplitude within the one-hour driving period. We assume that these changes indicate muscle fatigue as we did not observe significant correlations between movement behavior (indicated by the motion score) and muscular activity (Katsis et al., 2004; Sheridan et al., 1991).

An increase in muscle activity seemed to occur as a consequence of static low-level load the driving task, but the six-minute breaks at the end of the driving period were sufficient for recovery. During these breaks the drivers were still sitting, but it may well be that the drivers' positions during the breaks differed from their posture while driving. This may have caused the recovery. The typical driving posture is characterized by a restricted position due to the permanent need for control of the steering wheel and the pedals and the focus on the road (Gyi, 2013; van Veen & Vink, 2016). The presumable changes in position during the break may well have introduced a dynamic element which led to a relief from increased muscle activity. It seems interesting to note that a simple short break could have a positive effect that the application of a sophisticated seat-integrated stimulation designed to solve the muscle activity problem did not show. This finding is consistent with the results by Ding et al. (2020) showing that a passive break of 10 minutes during office work was effective in changing the muscles' state to non-fatigue states. During the passive break the participants remained seated. Ding et al. also showed that active breaks like having a walk or standing and stretching the body were even more effective than passive breaks.

However, truck drivers typically take neither active nor passive breaks during daily driving. Professional drivers' motivation to take additional breaks within their legally prescribed driving time is very low due to the lack of appropriate places to stop and their tight delivery schedules (Williamson & Friswell, 2013).

To remain competitive, most truck drivers in Europe use the maximum driving time of 4.5 hours, at the end of which a 45-minute break is required by law. After the break, they often drive non-stop for another 4.5 h (Nolle, 2006; Saltzman & Belzer, 2003).

This points to what is perhaps the biggest limitation of the present study. A continuous 4.5 hour driving task *without* breaks would have been closer to truck drivers' real-life situation, but this was not possible due to the technical limitations of the equipment we had available (see Experimental Design, Material and Procedure section). It is well possible that, without the recovery from increased muscle activity introduced by the six-minute breaks every hour, the effect of the seat-integrated stimulation on the sEMG amplitude may have become visible in the data. In fact, a closer inspection of Figures 4, 5 and 6 reveals that at a descriptive level there is a consistent advantage in terms of the sEMG amplitude of the stimulation condition relative to the no-stimulation condition in the fourth driving period. It thus seems possible that without breaks which truck drivers do not take in real life a reduction in sEMG amplitude and a beneficial effect of the seat-integrated stimulation may be observed.

This assumption is supported by the results of a previous study using the same seat-integrated stimulation that demonstrated positive effects on muscle stiffness and discomfort of long-haul truck drivers (Schneider et al., 2023). However, even though objective evidence of increased muscle load or fatigue could not be presented, the impact on the subjective comfort as a parameter of well-being is also of interest (Kyung et al., 2008) since increasing job attractiveness is seen as a central measure to alleviate the shortage of drivers (Federal Ministry for Digital and Transport, 2020). This includes, among other things, improving working conditions to attract potentially interested parties on the one hand and to retain employees in the long term on the other.

A further limitation of the present study is that, due to the use of a static truck simulator, there was a lack of whole body vibrations which might have reduced the effect of increasing muscle activity (Pope et al., 1998). Furthermore, the sitting position in a real truck might be different since steering wheel and pedals in the simulator differed to some degree. In future investigations, a continuous driving task under real driving conditions should be used to investigate possible effects prolonged driving muscle activity has on truck drivers.

The small sample size of the present study may also be considered a problem. It limits the size of the effects that can be detected. To illustrate this problem, we conducted a sensitivity analysis (Faul et al., 2007). In a sensitivity analysis, the size of an effect that can be detected in an experiment is calculated given a certain alpha error probability (typically $\alpha = .05$), a beta error probability (typically $\beta = .05$) and the sample size. The smaller the effect that can be detected, the more sensitive is the experiment. For simplicity, we focused on the difference between the levels of the test condition (stimulation condition – no-stimulation condition) as a function of the four levels of the driving period variable (driving period

1 to driving period 4) and ignored the sub-section variable. Our original main hypothesis was that the difference between the stimulation condition and the no-stimulation condition should be larger for later than for earlier driving periods because the seat-integrated stimulation should limit the increase in muscle activity as a function of the driving period variable in the stimulation condition relative to the no-stimulation condition. Given $\alpha = \beta = .05$, an assumed correlation among the difference scores of $\rho = .7$ (estimated based on the sampled data) and the $N = 14$ datasets we had available for the analysis of the sEMG data, effects of size $f = 0.32$ (i.e., between “medium” and “large” effects in terms of the conventions introduced by Cohen, 1988) could be detected. The goal to detect smaller than “medium” to “large” effects would require larger sample sizes.

The recording of muscle activity by means of sEMG should also be considered as a potential critical aspect. The quality of sEMG signals can be affected by various factors like the type of electrodes, interelectrode distances, blood flow, fat layer thickness and temperature of the muscles and the skin (Mohseni Bandpei et al., 2014). For these reasons the present study was conducted using a repeated-measures design and the electrodes were placed under a standardized sEMG protocol.

5. Conclusion

The present findings suggest that maintaining a sitting position during a 4.5 hour driving simulation does not result in an increased muscle activity of professional truck-drivers if driving is interrupted by short breaks. Within a continuous one-hour period, increased muscle activity can be observed, but breaks of the driving task as short as 6 minutes are sufficient to eliminate this effect. Contrary to our expectations, the seat-integrated stimulation had no significant impact on back muscle activity in the present study. It needs to be evaluated whether the seat-integrated stimulation has beneficial effects on muscle activity when prolonged driving of, for instance, 4.5 hours is not interrupted by breaks which is more typical of what truck drivers do in real life.

Authorship contributions

Please indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., Y.L. Cheung). The name of each author must appear at least once in each of the three categories below.

Category 1.

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Acquisition of data: L. Schneider, D. Sogemeier.

Analysis and/or interpretation of data: L. Schneider, D. Sogemeier.

Category 2.

Drafting the manuscript: L. Schneider, D. Sogemeier.

Revising the manuscript critically for important intellectual content: L. Schneider, D. Sogemeier, T. Jaitner, A. Buchner, N. Stutzig.

Category 3.

Approval of the version of the manuscript to be published (the names of all authors must be listed): L. Schneider, D. Sogemeier, T. Jaitner, A. Buchner, N. Stutzig.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Lisa Schneider reports financial support was provided by Daimler AG Group Research & Mercedes- Benz Cars Development. Lisa Schneider reports a relationship with Daimler AG Group Research & Mercedes- Benz Cars Development that includes: employment. Lisa Schneider has patent #DE 10 2018 000 765 A1 licensed to Daimler AG.

Data availability

The data that has been used is confidential.

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5.3. Auswirkungen eines sitzintegrierten Mobilisationssystems bei passiver Fahrerermüdung

Effects of a seat-integrated mobilization system during passive driver fatigue

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Abstract

Objective: The aim of this study is to evaluate the effectiveness of a seat-integrated mobilization system for maintaining vigilance under monotonous driving situations.

Method: For this purpose, vigilance indicators were compared intra-individually in a test condition with mobilization (seat-integrated stimulation) and a placebo condition under standardized conditions in a real driving study ($N = 31$). During a monotonous two-hour ride, physiological (brain activity by the EEG alpha spindle rate), performance-based (reaction times) and subjective indicators were recorded.

Results: The necessary precondition for the paradigm of inducing fatigue through monotony was confirmed by a significant increase in the EEG alpha spindle rate and the subjective vigilance indices. The mobilization system had a significant impact on the most fatigue-sensitive parameter of the alpha spindle rate, whereas the other parameters of vigilance did not reflect a significant effect of mobilization.

Conclusion: The *Mobilization Seat* is an effective measure to prevent drivers' fatigue during monotonous situations.

Keywords

Driver fatigue

Monotonous driving

Seat-integrated stimulation

Continuous EEG

Reaction time

Self- assessment

1. Introduction

Driver fatigue has been defined as a state of reduced physical or mental alertness, which typically occurs during prolonged monotonous driving situations (Williamson et al., 1996). It affects drivers' well-being negatively and has detrimental impact on driving safety. Professional drivers are particularly affected by this phenomenon due to the predominantly monotonous driving situations they are experiencing (Williamson et al., 1996). Driving on highways consists mainly of lane-keeping maneuvers, and provides little stimulation for the drivers, increases fatigue and decreases vigilance (Thiffault & Bergeron, 2003). Especially in this monotonous environment with little task demand, driving can be classified as a vigilance task. Mackworth (1956) defined vigilance as “the state of readiness to detect and respond to certain specified small changes occurring at random time intervals in the environment”.

Increasing automation intensifies the above mentioned effect since drivers are more likely to be cognitively removed from the driving process. At this point, it is necessary to distinguish between two types of driver fatigue, which depend on the driving task and the environment. While active fatigue due to high workload situations (e.g. high density traffic or poor visibility) can be potentially reduced by automation, passive fatigue, which mainly results from underload and monotonous situations is being enhanced by automation because the driver is mainly monitoring the systems without any active driving task (May & Baldwin, 2009; Saxby et al., 2013).

In the future, freight transport will continue to grow. According to the Prognos AG (2017), EU countries can expect a growth in goods transport of about 44 % between 2014 and 2040. As mileage increases,

in particular heavy commercial vehicles become more likely to be involved in an accident. Nevertheless, thanks to immense progress made by manufacturers, e.g. in the field of driver assistance systems, the number of traffic fatalities caused by commercial vehicle accidents throughout the EU has fallen significantly in recent years. In 2006, there were 7,233 road deaths. According to the EU Commission, this figure has fallen by over 47 % to 3,848 until 2015. However, when freight traffic vehicles are involved in accidents involving personal injury, the number of fatalities is disproportionately high (DEKRA Automobil GmbH). Based on 624 accidents in the database of the scientific study by the International Road Transport Union (2007), driver fatigue was the main cause in 6 % of the accidents, 37 % being fatal. However, since there is no reliable diagnostics tool for an applicable and objective measurement of fatigue, it is possible to determine fatigue only indirectly as accident cause (Kircher et al., 2002). Experts can only base their judgement on what they saw at the accident scene and what the drivers and witnesses told them. Therefore, it can be assumed that driver fatigue plays an even greater role in causing accidents.

Based on these findings, it is necessary to improve the safety of truck traffic and in particular to reduce the excessive demands placed on truck drivers. Many different vitalizing measures to promote road traffic viability have already been researched in the past (Gaspar et al., 2017; Gimeno et al., 2006). The most effective countermeasure against vigilance decrease is a nap of at least 15 minutes to a maximum of 30 minutes, which would require to interrupt the drive. However, with regard to professional drivers, the motivation for breaks beyond driving time regulations is very low due to economic reasons (Sagberg et al., 2004). The measures aiming to decrease driver fatigue which have been investigated so far have different advantages and disadvantages, and are usually recommended depending on specific situations; some are only effective for short periods of time (e.g. fresh air and listening to the radio), some are potentially harmful (e.g. substance-based measures) or some are being distracting (e.g. second tasks) (Cappelletti et al., 2015; de Valck & Cluydts, 2001; Greschner & Spath, 2011; Mets et al., 2011; Reyner & Horne, 1998; Schmidt et al., 2011). Rogé et al. (2003) observed that during simulated driving subsidiary body movements increase when vigilance decreases; it seems that micro-movements due to postural adjustments are also a natural countermeasure against fatigue. As a tactile stimulation, vibration of the safety belt only reduced fatigue for a short time (Greschner & Spath, 2011). By a haptic guidance steering system which continuously is exerting active torque on a steering wheel, driving performance on a monotonous driving course was significantly improved (Wang et al., 2017). Next to this Fitch et al. (2009) reported a decrease in reaction time using haptic seat alerts. Overall, it is very likely that offering variety to the monotonous driving task has a positive effect on task-related cognitive fatigue, especially when the stimulus is tactile.

Massage seats are also widely used in the automotive industry; however, mostly to increase seating comfort (Franz et al., 2011). Our *Mobilization Seat* investigated in this study was developed to counteract both, mental as well as physical effects of excessive sitting and driving. The objective is to

enhance road safety and to make the profession of truck driver more attractive. According to the research, physical fatigue due to sedentary behavior can be prevented by dynamic sitting (Lengsfeld et al., 2000; van Deursen et al., 2000) as well as by continuous passive motion (Pellettiere et al., 2006; van Deursen et al., 2000), the latter corresponding to dynamic passive stimuli. In addition, a study of Pellettiere et al. (2006) indicated that mechanical dynamic cushions (traditionally used to alleviate stress induced by prolonged wheelchair sitting) are also effective in improving performance and decreasing fatigue. The findings of Lee et al. (2020) also show that a motion seat with backrest recline, cushion tilt, and lumbar support inflation and deflation can be an effective countermeasure to reduce passive task-related fatigue. Furthermore, a study of Caldwell et al. (2003) indicates that postural manipulations (sitting and standing) are useful for counteracting fatigue in sleep-deprived individuals. Previous expert and customer surveys showed health promoting potential of the *Mobilization Seat* as well as a subjective increase in comfort. Furthermore, it was subjectively reported that the *Mobilization Seat* maintains vigilance longer (Daimler AG, 2018). The above findings show the large potential of this innovation to increase road safety through reducing fatigue-related accidents. The study at hand was conducted to verify and substantiate this assumption.

There are various methods of measuring driver vigilance, which differ in terms of reliability, validity, usability and effectiveness (Sparrow et al., 2019). They include physiological, performance-based and subjective measures to operationalize the hypothetical psychological construct of passive task-related fatigue.

A common physiological measurement for cognitive state assessment is provided by recording neuronal activities with electroencephalography (EEG). Lal und Craig (2001) identified the EEG as a promising method to measure the vigilance-related neural activity in the driving context, as it has a high degree of objectivity and a low degree of intrusiveness. The analyzed frequency bands of continuous EEG measurements are very susceptible to physiological artifacts, e.g. eyelid movements, as well as to technical artifacts. This susceptibility to artifacts makes sufficient data quality in real driving studies a major challenge. To mitigate this problem, Schmidt (2010) and Simon et al. (2011) proposed a new, more robust EEG parameter for recording driver fatigue. The so-called alpha spindles are occurrences in spontaneous EEG that were parameterized by Simon et al. (2011) via certain characteristics. They have been validated in numerous driving studies as highly sensitive parameters for fatigue detection (Schmidt et al., 2009; Schmidt et al., 2011; Simon et al., 2011). The studies showed that increasing fatigue was associated with an increase in the alpha spindle parameters (Schmidt, 2010). In addition, an increase in alpha-spindle rate correlated with a slowed braking response during the performance of an auditory secondary task (Sonnleitner et al., 2014). The advantages of alpha-spindle parameters as compared to generic alpha frequency band lies in its significantly lower susceptibility to artifacts caused by broadband noise and the higher sensitivity (Schmidt, 2010). Since the neurophysiological alpha spindle rate seems to be the most sensitive parameter for recording vigilance decrement in driving

studies during monotonous driving (Simon et al., 2011), this operationalization of vigilance forms the main assumption of the present study.

In applied research, reaction time (RT) represents a central performance measure and is becoming highly relevant in the context of accident prevention, especially for professional duties which demand high concentration and high accuracy (Bäumler, 2009; Graw et al., 2004). As an objective measure of performance during sustained attention tasks, RT of test subjects was tested before and after the test drives with the Psychomotor Vigilance Task (PVT) (Dinges & Powell, 1985). The 10 % fastest and slowest RTs were considered separately, since the slowest reactions are mostly affected by vigilance decrement (Graw et al., 2004). Attention gaps (eyelids closing or even microsleep) can be sufficiently compensated, resulting in normal RTs for a short period of time and does not affect performance in the fastest RTs (Anderson et al., 2010). This operationalization of vigilance forms the second assumption.

Since the majority of vehicles currently in use do not have an automatic fatigue warning system installed so far, drivers must decide for themselves when they should take a break from driving. Therefore, their own subjective assessment of vigilance is important. This measure can be recorded using validated scales during, as well before and after the journey. The *Karolinska Sleepiness Scale* (KSS) by Åkerstedt und Gillberg (1990) is the most widely used scale for measuring situational state fatigue. The good predictive validity of this nine-point Likert-type scale was confirmed by a number of physiological and performance-based measurements of fatigue and correlated with accident risk in simulator and real driving studies (Åkerstedt et al., 2014; Hallvig et al., 2013). The *Tiredness Symptoms Scale* (TSS) by Schulz et al. (1991) is an instrument to record sensations typically associated with tiredness. It subjectively measures the feeling of 14 fatigue symptoms, such as burning eyes, shivering, yawning, disinterest or the urge to move. Although the advantage of subjective measures lies in their user-friendliness and practicability, they usually do not capture the objective level of fatigue, as people tend to misjudge (Schmidt et al., 2009).

In summary, we investigated the effectiveness of the seat-integrated mobilization system as a means to maintain vigilance under monotonous driving situations. It was hypothesized that mobilization causes a reduction in fatigue-related parameters derived from physiological measures, performance-based measures and subjective measures.

2. Material and Methods

2.1. Mobilization Seat



Figure 1: Mobilization Seat

The *Mobilization Seat* (figure 1) was developed in the research department of Mercedes-Benz AG and has been patented under number DE 10 2018 000 765 A1. It generates dynamic passive stimulation by inflating and deflating 14 air cushions in the backrest and 4 air cushions in the seat. The iteratively developed and in driving studies tested programs include four different mobilization sequences, whereby the air cushions are inflated differently (Daimler AG, 2018). By means of the different sequences, the different body segments are being moved dynamically in different directions in order to promote dynamic sitting. In addition, breaks between sequences are used to provide variety.

2.2. Participants

For the central alpha spindle hypothesis, a priori statistical power analysis with *G*Power* (Faul et al., 2007) was performed for the effect of the measuring-repeated variable *test condition*. With a sample size of $N = 31$, a medium-sized effect of $f = .33$ was found at $\alpha = .05$ (Cohen, 1988; assumed correlation of the steps of the measurement repeated variable $\rho = .50$, probability $1-\beta = .95$).

Thirty one male participants (age: $M = 45$, range: 25 - 60) with adequate truck driving experience (average annual driving distance of approximately 5,000 km/ 3,100 miles per year) were recruited on a voluntary basis. This corresponds to a rather irregular driving practice; however, due to the low demands on the drivers it was sufficient for the driving task to be performed. Since a gender balance was not achievable in recruitment and approximately 98 % of the professional drivers in Germany in

recent years were male (Bundesamt für Güterverkehr, 2019), only men were recruited to participate in the study. In order to control confounding variables, the subjects were instructed to behave as similarly as possible to their individual everyday life on the two days prior to the study. In addition, the subjects were instructed to refrain from drinking caffeine starting 1.5 hours prior to the study.

2.3. Experimental design

To increase ecological validity, the experiment was conducted under close to real driving conditions. Due to strong inter-individual differences in fatigue susceptibility (Dongen et al., 2004), the driving study was conducted with a within-subject-design. All participants underwent two experimental conditions on different survey days, consisting of a placebo condition and an experimental condition. The experimental condition consisted of the activation of the seat-integrated mobilization system, whereas the placebo condition was created by a simulated scenting of the driver's cabin. In order to control sequence effects, the test persons ran through these experimental conditions randomly.

On one test day two data sets were collected simultaneously in the morning and in the afternoon. In this two-shift operation two participants arrived at the lab at 08:00 a.m. and at 01:00 p.m. the other two participants arrived. The subjects had to pass through the two surveys on separate days and were measured at the same time of day to avoid circadian influences.

before the drive (pre-measurements)	<ul style="list-style-type: none"> • Tiredness Symptoms Scale (TSS) • Psychomotor Vigilance Task (PVT)
during the drive	<ul style="list-style-type: none"> • Continious electroencephalogram (EEG) • 3 x Karolinska Sleepiness Scale (KSS) • 3 x Assessment of situational alertness (ATT) • 3 x Assessment of situational monotony of driving (MON)
after the drive (post-measurements)	<ul style="list-style-type: none"> • Psychomotor Vigilance Task (PVT) • Tiredness Symptoms Scale (TSS)

Figure 2: Chronological sequence of measurements

The chronological sequence of the measurements is shown in figure 2. To exclude influences of the sleep duration, we queried these respectively. While the physiological recording equipment was applied, the participants completed the TSS. Before starting the test drive, test persons were asked to complete the 10-minute pre-measurement of the reaction time test PVT in the truck alone. Participants practiced the PVT reaction time test prior to the measurement, in order to eliminate differences between the pre- and post-measurement by learning effects. The experimental condition was a monotonous driving

situation. During the survey, the trucks were driven 2 hours with an adaptive cruise control behind a leading vehicle, thus forming a convoy task similar to real motorway driving situation. As you can see in figure 3 and figure 4, the topography of the non-public ring road (36km) with its numerous bends and inclines would have been too demanding at the permitted maximum speed of 80 km/h, the driving speed was set to 35 km/h.



Figure 3: Truck convoy on the non-public ring road

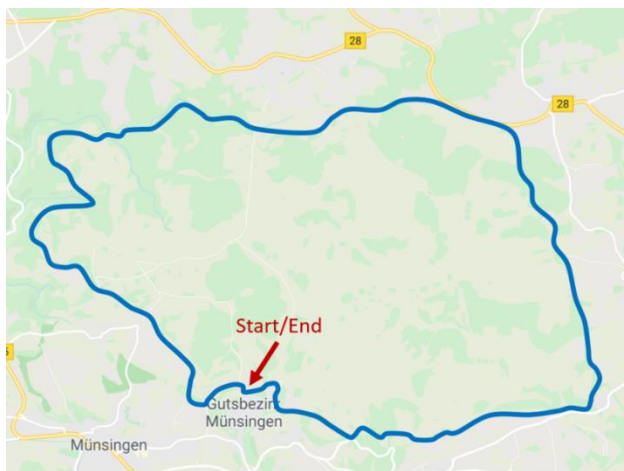


Figure 4: Course of the test track in Münsingen (Germany) from Google Maps

Two identical Mercedes-Benz trucks (Daimler AG) of the Actros 1845 LS series were used as test vehicles and their trailers were loaded up to the maximum weight of 40 tons to maintain the ecological validity. To prevent alerting effects no passengers were present during the test drive (Hallvig et al., 2013). The self-assessment requests (KSS, ATT, MON) appeared thrice at fixed times during the drive: 10 minutes after start, 60 minutes after start (halfway) and after 110 minutes. Since the test subjects were alone in the vehicle, the items were queried via a tablet PC on the truck dashboard. In order not to affect driver fatigue, drivers were not allowed to listen to the radio, chew chewing gum or switch on seat heating or ventilation during the experiment. They were also asked to keep the air conditioning at

a preset of 21 degrees. After the 2-hour test drive, the test supervisors entered the trucks and handed the subjects the material for the post-measurement of the PVT. As a final step, the TSS was filled out.

2.4. Physiologic measures

Based on Schmidt (2010) and Schmidt et al. (2011), a mobile EEG (Timm, 2019) was derived from the test subjects during the test drives to record the alpha spindles occurring with the 10/20 electrode system according to (Jasper, 1958). For this purpose, a 16-channel BrainVision system (BrainProducts GmbH, Munich, Germany) with active electrodes and the wireless EEG/EXG LiveAmp amplifier was used.

2.5. Performance-based measures

In order to assess performance-based measures, the Psychomotor Vigilance Task Software (PC-PVT 2.0) (Reifman et al., 2018) was installed on two laptops. As a stimulus, a millisecond counter of the reaction time appeared in red writing in the middle of a black screen with a randomized interstimulus interval of 2 to 10 seconds, so that the test subjects received feedback on their speed at each reaction. Following the software's recommendation, the reactions were carried out by pressing a button with the index finger of the dominant hand on a Logitech G203 gaming mouse (8,000 DPI). A rigid mousepad was used to place the gaming mouse on the subject's leg. Reaction times were recorded with a 1 kHz resolution. To maintain the monotony while driving, the RT was captured before and after the test drive. In order to record the reaction times as close as possible to the test drive, the tests were carried out in the truck's driver cabin.

2.6. Subjective measures

The TSS by Schulz et al. (1991) assesses 14 subjective fatigue symptoms such as burning eyes sensations, frosting, yawning, lack of interest or urge to move. Using the KSS of (Åkerstedt & Gillberg, 1990), the subjects were repeatedly asked to rate their situational alertness on the nine-point Likert-type scale during the test drives. In addition, two further scales for the ATT and MON were queried (Schmidt et al., 2009).

2.7. Primary and secondary measures, control variables



Figure 5: Primary and secondary measures

Figure 5 shows the primary and secondary measures of the study with the corresponding measuring method. As primary measure for driver fatigue we used the alpha spindle rate. According to our hypothesis the alpha spindle rate should increase significantly over the test drives and significantly differ between placebo and experimental condition. Furthermore, we hypothesized that the experimental condition shows a significantly lower alpha spindle rate.

Our secondary measures included the RTs and the symptoms of fatigue before and after the test drive. For this, we assumed that the RTs after the test drives are significantly slower than before the test drives due to vigilance decrement. This deceleration is hypothesized significantly lower in the experimental condition than in the placebo condition. In the individual surveys, we hypothesized that the number of self-estimated fatigue symptoms after the test drives is significantly higher than before the test drives due to vigilance decrement. We assumed that the increase in fatigue symptoms are significantly lower in the experimental condition than in the placebo condition. Further secondary outcomes included the rates of the current alertness on the KSS, the inattentiveness on the ATT and the monotony of the ride on the MON over the course of the ride. We hypothesized that these rates increase significantly over the course of the journey and differ significantly between the conditions. We expected that the experimental condition shows a significantly lower increase.

In addition, several vehicle data were recorded in order to identify specific driving maneuvers for further analysis and considerations.

2.8. Pre-processing

EEG raw data were pre-processed with *BrainVision RecView 1.4.3* and *BrainVision Analyzer 2.2.0* (*BrainProducts GmbH*). To remove artifacts, an Infinite Impulse Response (IIR) filter was applied (Low cutoff at 0.53 Hz, time constant 0.3, High cutoff of 35 Hz, filter order 2). Data were filtered with 50 Hz notch filter to attenuate electrical noise. Subsequently, the software's own eye artifact correction *Ocular Correction* was applied. After the data correction, the *Daimler spindle detector* integrated as

macro was applied (Simon et al., 2011). The *Daimler Spindle Rate 60* function calculated the average alpha spindle rate in a 60-second sliding window with a step size of 1 s over the driving time. Then the resulting alpha spindle rate with a resolution of 1 Hz was exported. For the statistical analysis the mean value of the spindle rate was calculated for three equal blocks (40 minutes) at the beginning, in the middle and at the end of the drive.

For the pre-processing of the PVT reaction time data, the mean reaction time, the 10 % fastest and the 10 % slowest reactions times were extracted. Since in accordance to our hypothesis, changes from pre- to post-measurement were of interest, we calculated the difference between pre- and post-values. Thus, a positive difference corresponded to a reaction time decrease and a negative difference to an acceleration.

The data of the KSS, ATT and MON tests were analyzed by SPSS. For the data pre-processing of the TSS, the achieved sum value on the scale first had to be calculated manually. Then the differences between the pre- and post-measurements were calculated by subtracting pre- from post-measurements; thus, positive differences corresponding to an increase and negative ones to a decrease in fatigue symptoms.

2.9. Statistical Analysis

In a preliminary exploratory analysis, all variables generated in the data pre-processing were checked for the presence of the normal distribution using the Kolmogorov-Smirnov test. In order to exclude confounding effects of the time of day of the survey on the independent variable of the test condition, mixed-model analysis of variance (mixed-model ANOVAs) were calculated for each dependent variable with the within-subject factor *test condition* (placebo condition and experimental condition) and the within-subject factor *daytime* (morning and afternoon block) before the actual statistical analysis.

The alpha spindle hypothesis was tested for significant main effects and interactions using multivariate analysis of variance (MANOVA) according to O'Brien und Kaiser (1985) with the within-subject factor of the *travel block* (beginning, middle and end) and the within-subject factor of the *condition* (placebo condition and experimental condition). For the self-assessment hypothesis, the same analysis method was applied in accordance with the experimental design. Both, the reaction time hypothesis and the fatigue symptom hypothesis were tested for significant effects using repeated measures ANOVA with the within-subject factor *condition* (placebo and experimental condition) and the differences of the pre- and post-measurements within the *test condition* as dependent variable. The *p*-value of the constant term in the tests of the between subject effects indicated whether the individual differences of the measurements differed significantly from 0, and thus, whether there was any change at all due to the

test drive. The level of α was set to .05 for all analysis. Whenever H_0 had to be rejected, the partial η_p^2 is reported as a measure of relative effect size.

3. Results

Four EEG data sets were removed from further analysis due to low data quality (if impedance was less than 10 k Ω during recording), five reaction time data sets as well as two self-assessment data sets were removed due to recording problems. The criterion of normal distribution was fulfilled for the data of the central alpha spindle hypothesis, but was violated for individual variables of the four secondary hypotheses. However, since repeated measures of ANOVA are considered robust against normal distribution violations according to Wilcox (2012), the use of nonparametric procedures to replace parametric analysis of variance was abandoned.

The mixed-model ANOVA with the within-subject factor *test condition* and the between subject factor *daytime* showed no significant main effects or interactions (smallest $p = .392$) in the central alpha spindle hypothesis.

The mean difference in sleep duration of all subjects in the two previous nights of the surveys was 0.27 hours (SD = 1.01), with a maximum difference of 3 hours. Since the subject with a sleep difference of 3 hours in the two previous nights does not form an outlier in the dependent variables, he could be included in the evaluation.

3.1. Physiologic measures

The average alpha spindle rate as a function of different test conditions is shown in figure 6. In order to show a more detailed time-on-task effect, each of the conditions is divided into three equal travel blocks (each 40 minutes). In the MANOVA measurements, significant main effects of the within-subject factors *travel block*, $F(2, 25) = 20.73, p < .001, \eta_p^2 = .62$ and *test condition*, $F(1, 26) = 4.46, p = .044, \eta_p^2 = .15$ were found. The interaction between the factors was not significant ($p = .084$). Thus, within the experimental conditions, the average alpha spindle rate increased significantly over the three blocks of drive, so that it can be assumed that the objectives of the present paradigm of generating monotony and vigilance decrement were achieved. The fact that the increase in the alpha spindle rate corresponds to a linear trend over a certain duration of travel (Schmidt et al., 2009) was also confirmed in this travel study, $F(1, 26) = 40.68, p < .001, \eta_p^2 = .61$. Furthermore, in all three travel blocks, the alpha spindle rate was significantly lower in the experimental condition than in the placebo condition.

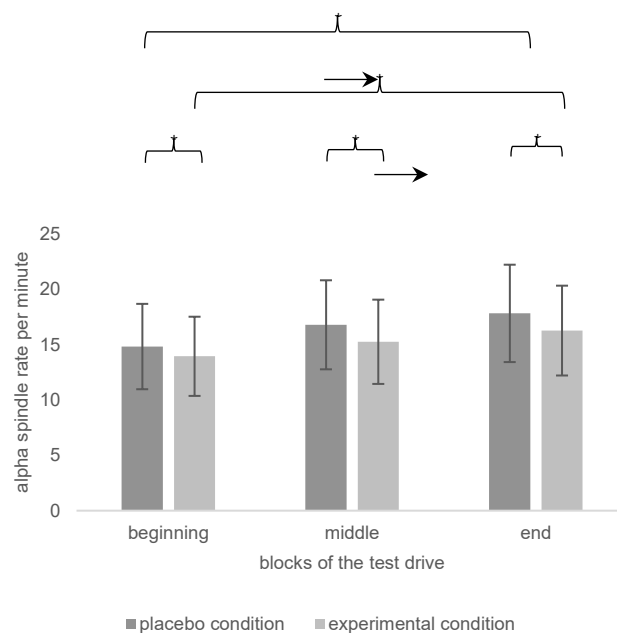


Figure 6: Average alpha spindle rates per minute over three 40-minute blocks of the test drive depending on the test conditions ($n = 27$). The error bars represent the standard deviation of the mean values. * $p < .05$

3.2. Performance-based measures

For the three reaction time variables of the mean reaction time, the 10 % fastest and the 10 % slowest reactions, repeated measures ANOVAs were calculated with the within-subject factor of the *test condition* and the differences of the pre- and post-measurements.

The difference in mean reaction time from pre- to post-measurement did not differ significantly between the placebo and experimental conditions ($p = .658$). Even when the differences of the 10 % fastest ($p = .560$) and 10 % slowest reactions ($p = .558$) were considered separately, no significant effects were found.

As expected, the difference of the mean reaction time, $F(1, 25) = 8.15, p = .009, \eta_p^2 = .25$, and the difference of the 10 % fastest reactions $F(1, 25) = 15.81, p = .001, \eta_p^2 = .39$ differed significantly from zero, so that a change occurred in these reaction time variables due to the test drive. This was not confirmed for the differences of the 10 % slowest reactions ($p = .507$). On the basis of the positive differences of the descriptive data shown in figure 7, a slight slowing down of the reaction times can be seen on average by completing the test drive.

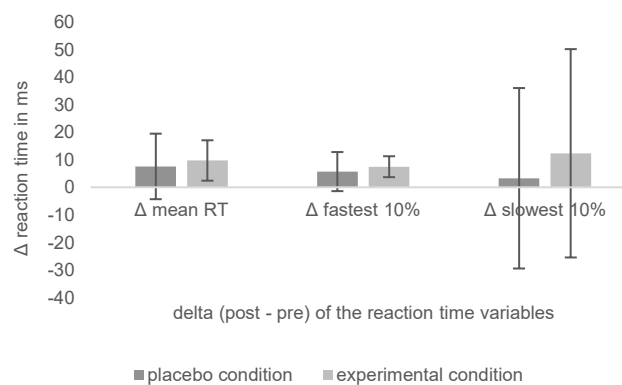


Figure 7: Mean differences from post- to pre-measurement of the reaction time variables of the mean reaction time (RT), the fastest 10 % and the slowest 10 % of the reactions depending on the test conditions ($n = 26$). The error bars represent the standard deviation of the mean values.

3.3. Subjective measures

Over the three self-assessment scales, each of the MANOVAs showed a significant main effect of the driving block factor, as expected. The subjective rating shows a significant increase over the course of the ride for all three measures:

KSS, $F(2, 27) = 34.50, p < .001, \eta_p^2 = .72$; ATT, $F(2, 27) = 36.50, p < .001, \eta_p^2 = .73$;

MON, $F(2, 27) = 49.49, p < .001, \eta_p^2 = .79$. However, contrary to the self-assessment hypothesis, the main effect of the experimental condition or interaction was not significant on any of the three scales (smallest $p = .317$). The descriptive statistics associated with the inferential statistics illustrate these findings in figure 8.

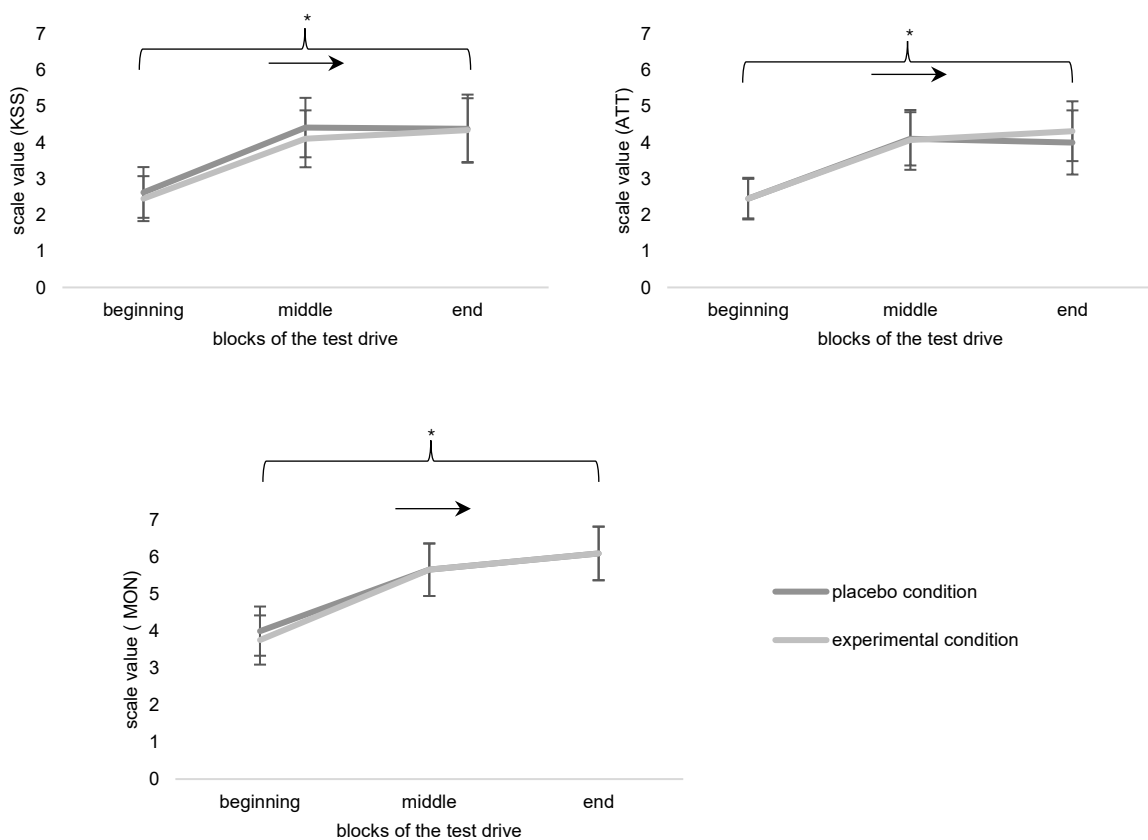


Figure 15: Mean scale values of the self-assessment (KSS, ATT and MON) over the time course of the test drive as a function of the test conditions ($n = 29$). The error bars represent the standard deviation of the mean values. $*p < .050$

The second hypothesis to be examined on the subjective level was the hypothesis on fatigue symptoms. Equivalent to the evaluation of the reaction time data, the differences of the pre- and post-measurements were examined statistically according to the experimental conditions. Contrary to expectations, the repeated ANOVA measurements did not show any significant difference in the differences between the different test conditions ($p = .572$). The differences within the test conditions,

however, differed significantly from zero, $F(1, 30) = 16.93, p < .001, \eta_p^2 = .36$. Accordingly, an increase in fatigue symptoms can be confirmed over the 2-hour driving course. On average, the subjects showed more fatigue symptoms after the test drive in the placebo condition 1.29 ($SD = 2.19$) and in the experimental condition 1.13 ($SD = 1.34$).

Descriptively, a slight difference can therefore be seen in figure 9. The increase in fatigue symptoms was slightly lower in the experimental condition than in the placebo condition.

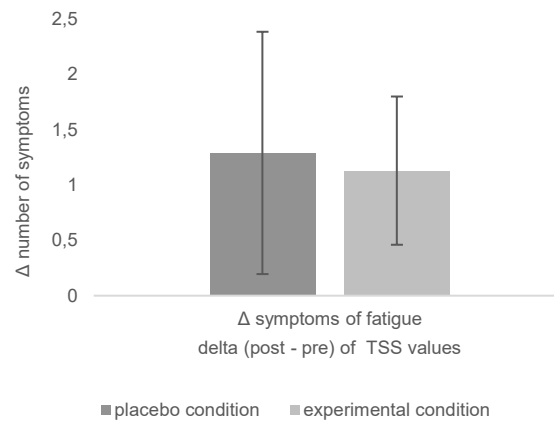


Figure 16: Mean scale values of the self-assessment (TSS) ($n = 31$). The error bars represent the standard deviation of the mean values.

4. Discussion

4.1. Physiologic measures

The results of the study confirmed that the alpha spindle rate increases over the course of the journey and is reduced by seat-integrated passive mobilization. Furthermore, the significant increase of the alpha spindle rate over the 2-hour ride in both test conditions shows that the goal to generate passive task-related fatigue by the monotonous driving task has been achieved. This is particularly important for the generalizability of the results to the currently targeted application area of professional drivers. The reduced driving time of 2 hours, in contrast to the 4.5 hours prescribed by the Regulation (EC) No 561/2006 (in Europe) leads to a comparable degree of fatigue as with long motorway trips. In the experimental condition with an activated mobilization system, there was also an increase in fatigue during the test drive, but, in accordance with the hypothesis, the average alpha spindle rate in all three drive intervals was significantly lower than in the placebo condition. This indicates that the test subjects were kept more attentive and less fatigued by the physical mobilization during the monotonous driving situation than in the placebo condition. According to the correlation between the alpha spindle rate and the braking response demonstrated by Sonnleitner et al. (2014), it could be implicitly assumed that the *Mobilization Seat* may have a positive effect on the driving performance. The significant difference already at the beginning of the test run suggests at first sight a baseline difference in the alpha spindle rate depending on the test condition. However, it is conclusive that the mobilization was already effective in the first 40-minute interval. The descriptive data shows that the difference between the test conditions becomes bigger during the course of the journey due to the activating effect of the mobilization. Therefore, and because of the proven linear increase in the alpha spindle rate, we assume an even greater effect of the integrated seat with longer travel time. However, this assumption should be investigated in further research.

4.2. Performance-based measures

The slowing of reaction times did not differ significantly between experimental conditions for any of the individual variables. Although the difference in the mean reaction time and the fastest 10 % of the reactions deviated significantly from zero, no systematic change between the pre- and post-surveys was observed in the parameter of the 10 % slowest reactions, which according to earlier findings was the most sensitive parameter (Graw et al., 2004). Accordingly, the reaction time hypothesis must be rejected, too. Concerning the performance of the reaction time test, it is to be assumed that the successful completion of the ride concealed the vigilance decrement. This effect describes a sudden increase in alertness as well as attention in form of joy and relief at the end of a ride. Schmidt et al. (2009) also showed this activation at the end of the test drives in the variables collected here. The

present test set-up favored this activation by the reaction time testing before and after the test drives. The necessary interaction with the test supervisors to start the post-test in the truck had an additional strengthening effect, even if they tried to limit communication to the most necessary. After the monotonous 2-hour test drive, most of the test persons conveyed a relieved impression and a high need for communication.

4.3. Subjective measures

The information provided by the test subjects on the subjective scales reveal a significant increase in fatigue and perceived monotony during the individual test drives, as shown in figure 8. In line with the EEG findings, these hypothesis-conform results also support the successful generation of typical driver fatigue during long-distance driving by the chosen paradigm. In contrast to our hypothesis, no effect was found on the subjective level on any of the used scales with regard to the experimental manipulation by the *Mobilization Seat*. The nine-point Likert-type scales KSS, ATT and MON appear to be suitable for recording a vigilance decrement while driving, but they may be too coarse for recording the difference between the experimental conditions caused by mobilization. Furthermore, repeated subjective data are within a few hours influenced by strong anchor effects, since the test subjects can usually remember their data from previous queries (Tversky & Kahneman, 1974). As mentioned above, people's subjective statements regarding their attention status do not necessarily correspond to objective measurements (Schmidt et al., 2009). Furthermore, different methods of measuring driver fatigue show a rather low congruent validity to each other (Sparrow et al., 2019). The same problems can also be assumed for the 14-level TSS score; the physiological measurements of vigilance should therefore be given more weight in the interpretation of the findings. Nevertheless, due to the small additional effort and as feedback on the sensation of the test persons, it is worthwhile to include subjective variables in driving studies. In the future, e.g. stepless visual analogue scales could be used to record a difference in the degree of fatigue (Ahearn, 1997).

In summary, for the findings concerning the main and secondary hypotheses, it can be stated that the high sensitivity of EEG alpha spindle measurements for fatigue effects under real driving conditions according to (Schmidt, 2010) could be successfully replicated. The finding that only the central alpha-spindle hypothesis showed a significant difference in experimental conditions supports Schmidt's assumption that the alpha-spindles are the most sensitive parameter for recording vigilance in the driving context.

4.4. Limitations

In order to standardize and control the traffic situation, the effects of the *Mobilization Seat* were investigated on a non-public test area. Due to the varied topography of the ring road, the general conditions corresponded only to a limited extent to the typical motorway conditions on European roads. The untypical truck speed and road topography limited the ecological validity. In addition, the reduction of the legal maximum driving time from 4.5 hours to 2 hours of driving time has to be critically reflected. However, the recorded measures show that the experimental design successfully induced a significant increase of fatigue after 2-hours of driving. The subjective feedback of the test persons confirmed that a longer driving time would have led to a significant increase in the safety risk and to fatigue-related aborts of the test drives. Overall, data quality was good since only an acceptable portion of the recordings had to be removed due to technical difficulties. Our multi-level approach to assess fatigue was confirmed since the measurement methods detected an increase in fatigue, however, with different sensitivities. In order to ensure generalizability to real road traffic and professional drivers, a replication of the study needs to be carried out, however, taking into account disadvantages due to poor controllability of experimental conditions such as surrounding traffic. Furthermore, only male subjects participated in the present study, which is why the generalizability to female drivers can be critically questioned. However, no gender differences have been found in past research on driver fatigue. In the future, a replication with female and male test persons could be envisaged in order to completely exclude a gender difference with regard to the effectiveness of mobilization during driving. Due to the predominant share of men in the occupational group of professional drivers, however, this limitation is almost negligible for the generalizability to the target group.

4.5. Research outlook

Since bus and car drivers also have to make monotonous long-distance journeys and will be affected by increasing automation, a transfer of the seat-integrated mobilization system to other vehicle types would be conceivable. Since subjective assessment of driver fatigue does not necessarily correspond to objective measurements (Schmidt et al., 2009), it is recommended to link the activation of the mobilization system with a fatigue detection system. E.g., the Attention Assist (Daimler AG) could suggest to the driver to activate the *Mobilization Seat* when a slight vigilance discrepancy is detected, before an interruption of the journey is requested in case of advanced fatigue.

5. Conclusion

The number of road users and the time and economic pressure, especially for professional drivers, will increase significantly in the coming years. In order to reduce the risk of accidents, newly developed vehicles will increasingly be equipped with driver assistance systems, which already allow partially automated driving. Until full autonomy is achieved, humans will have to act as the monitoring instance of the technical systems and take over the control of the vehicle in an emergency. Due to the lack of active involvement, monitoring may induce more fatigue than manual driving (Schömig et al., 2015). Therefore, it is desirable to intervene in an early stage of the fatiguing process to decrease the perceived load from a monotonous driving task and to create a more pleasurable driving experience. Many researched countermeasures for increasing fatigue have limited effects or are limited in their applicability. In the present study, a stimulation with air cushions in the driver's seat was to be evaluated as a potential new countermeasure to the vigilance decrement. Further effects of the seat on physical fatigue have to be investigated. As a final evaluation, it can be stated that the newly developed, seat-integrated mobilization system of Mercedes-Benz AG was able to improve the vigilance of the test subjects, operationalized via the fatigue-sensitive alpha spindles, in the real-life truck driving study conducted under a monotonous and partially automated driving situation. This finding on mobilization is considered a new approach to the numerous researched countermeasures for passive, task-related fatigue in the driving context and can contribute to a sustainable increase in traffic safety.

Declaration of Competing Interest

There are no conflicts of interest.

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6. Abschlussdiskussion

Ziel der vorliegenden Arbeit war die Gesundheits- und Bewegungsförderung von Berufskraftfahrenden. Hierfür wurde ein sitzintegriertes Mobilisationssystem anhand biomechanischer, physiologischer und subjektiver Parameter evaluiert. Untersucht wurde, ob die pneumatische Aktivierung von Luftkissen das Potenzial besitzt, die physiologische Beanspruchung und die kognitive Ermüdung von Berufskraftfahrenden zu verringern.

Zur Beantwortung der ersten Forschungsfrage – *Verringert das sitzintegrierte Mobilisationssystem die physiologische Beanspruchung von Berufskraftfahrenden?* – wurde das Potenzial des sitzintegrierten Mobilisationssystems als gesundheitsfördernde Maßnahme experimentell untersucht. Hierfür wurden Bewegungsaktivität, Muskelsteifigkeit, Diskomfort sowie die Aktivität der Rückenmuskulatur von 16 Fernkraftfahrenden während einer viereinhalbstündigen simulierten Fahraufgabe intraindividuell in einer Mobilisations- und Kontrollbedingung erfasst. Die Ergebnisse zu Bewegungsaktivität, Muskelsteifigkeit und Diskomfort wurden von Schneider et al. (2023b) veröffentlicht (vgl. Kapitel 5.1), die Ergebnisse zur Aktivität der Rückenmuskulatur von Schneider et al. (2023a) (vgl. Kapitel 5.2).

Zur Beantwortung der zweiten Forschungsfrage – *Verringert das sitzintegrierte Mobilisationssystem die kognitive Ermüdung von Berufskraftfahrenden?* – wurde das sitzintegrierte Mobilisationssystem im Rahmen einer Realfahrstudie unter standardisierten Bedingungen hinsichtlich seiner vigilanzerhaltenden Wirkung untersucht. Dabei wurden physiologische und subjektive Vigilanzindikatoren von 31 Versuchspersonen intraindividuell in einer Mobilisations- und einer Kontrollbedingung erhoben. Die Ergebnisse zur Alpha-Spindel-Rate, zur Reaktionszeit sowie zu den subjektiven Einschätzungen wurden von Schneider et al. (2021) veröffentlicht (vgl. Kapitel 5.3).

Die in Kapitel 5.1 und 5.2 dargestellten Ergebnisse zeigen, dass pneumatische Mobilisationsfunktionen einen Einfluss auf die physiologische Beanspruchung von Berufskraftfahrenden haben können. Die Luftkissen der sitzintegrierten Mobilisationsfunktion führten nachweislich zu einer erhöhten Bewegungsaktivität, wie die Erfassung mittels Inertialsensorik belegt. In der Mobilisationsbedingung wurde eine signifikant höhere Bewegungsaktivität festgestellt. Wie in Kapitel 3 beschrieben, kann dynamisches Sitzen positive physiologische Effekte haben und zur Reduktion von LBP infolge sedentären Verhaltens beitragen (van Deursen et al., 2000). Nach Hermann und Bubb (2007) führen lange Sitzperioden zu Umsetzbewegungen als Reaktion auf Druckbelastung. In der Mobilisationsbedingung wurden signifikant weniger dieser Bewegungen detektiert, was auf eine geringere Druckbelastung und damit auf ein reduziertes Diskomfortempfinden hinweist. Auch die subjektiven Angaben der Teilnehmenden bestätigten dies: In der Kontrollbedingung wurde signifikant häufiger Diskomfort angegeben. Wiederholter Diskomfort kann langfristig zu Schmerzen führen, wie Hamberg-van Reenen et al. (2008) in einer Längsschnittstudie zeigten. Schmerzen wie LBP stehen in

direktem Zusammenhang mit einer erhöhten Muskelsteifigkeit (Masaki et al., 2017). In der Kontrollbedingung zeigte sich während einer viereinhalbstündigen simulierten Fahrt ein signifikanter Anstieg der Muskelsteifigkeit im LWS-Bereich (gemessen mittels Myometrie). Hypothesenkonform blieb dieser Anstieg in der Mobilisationsbedingung aus. Im BWS-Bereich blieb die Muskelsteifigkeit in der Kontrollbedingung nahezu konstant, während sie in der Mobilisationsbedingung signifikant reduziert werden konnte. Eine erhöhte Muskelsteifigkeit kann auf eine eingeschränkte Mikrozirkulation im Muskel hindeuten (Yoshitake et al., 2001). Der gestörte Blutfluss führt zu einer unzureichenden Sauerstoffversorgung, was die Entzündungsregulation hemmt und die Akkumulation von Stoffwechselprodukten begünstigt (Kell & Bhambhani, 2008; McGill et al., 2000). Die Aktivierung der Luftkissen und die damit verbundene Unterbrechung statischer Sitzhaltungen könnte somit die Mikrozirkulation im Muskel verbessern und eine mögliche Schmerzentwicklung verhindern. Auch die EMG-Daten (Elektromyografie-Daten) stützen diese Annahme. Das EMG ist ein Verfahren zur Messung der elektrischen Aktivität von Muskeln und ermöglicht Rückschlüsse auf Muskelaktivierung und -ermüdung. In dieser Studie wurde die Aktivität der Rückenmuskulatur – insbesondere des *M. trapezius pars descendens*, *M. trapezius pars ascendens* und *M. erector spinae* – analysiert. Der signifikante Anstieg der Amplitudenwerte innerhalb der einstündigen Fahrtblöcke deutet auf eine muskuläre Ermüdung hin (Allen et al., 2008; Luttmann & Jäger, 2013). Die Aktivierung der Rückenmuskulatur scheint notwendig zu sein zur Stabilisierung der Sitzhaltung während der Fahrt. Da keine signifikante Korrelation zwischen Bewegungsaktivität und EMG-Amplitude festgestellt wurde, ist von einer tatsächlichen Muskelermüdung auszugehen. Obwohl die gemessenen Muskelkontraktionen mit 0,8 % der MVC (Maximale Willkürliche Kontraktion) im *M. trapezius pars descendens* und bis zu 2,5 % im *M. erector spinae* sehr gering waren, kann selbst bei diesen Werten eine Minderdurchblutung auftreten (McGill et al., 2000), insbesondere wenn der intramuskuläre Druck den Perfusionsdruck übersteigt (Sejersted et al., 1984; Sjøgaard et al., 1986; Wesche, 1986). Die EMG-Analyse der untersuchten Muskeln zeigte innerhalb der einstündigen Fahrtblöcke einen signifikanten Anstieg der Amplitudenwerte. Über die gesamte Fahrdauer hinweg war dieser Anstieg jedoch nicht signifikant. Unterbrechungen der Fahraufgabe reichten aus, um diese Effekte zu kompensieren. Zukünftige Studien sollten daher längere, ununterbrochene Fahrten (z. B. über viereinhalb Stunden) untersuchen, um potenzielle Effekte auf die Muskelaktivität besser erfassen zu können. Entgegen den Erwartungen unterschieden sich die EMG-Amplitudenwerte zwischen den Versuchsbedingungen nicht signifikant. Effekte der Mobilisation auf die Muskelaktivität wie in früheren Studien von Kolich et al. (2000) und Franz et al. (2011) konnten demnach nicht festgestellt werden. Dieses Ergebnis unterstreicht die Relevanz des multimethodalen Untersuchungsansatzes dieser Arbeit.

Langes Sitzen beeinträchtigt nicht nur die Durchblutung der Rückenmuskulatur, sondern auch die zerebrale Durchblutung. Carter et al. (2018) zeigten, dass längere Sitzzeiten mit einer Minderdurchblutung des Gehirns einhergehen, was wiederum die kognitive Leistungsfähigkeit negativ

beeinflussen kann. Dies bestätigen die Ergebnisse der Realfahrstudie (vgl. Kapitel 5.3). In der Kontrollbedingung zeigte sich während der zweistündigen Kolonnenfahrt ein signifikanter Anstieg sowohl der Alpha-Spindel-Rate als auch der subjektiven Vigilanzindikatoren – ein Hinweis auf passive Ermüdung infolge monotoner Fahrsituationen. Die konstante Geschwindigkeit von 35 km/h mit aktiviertem Abstandsregeltempomat reichte aus, um diese Effekte zu induzieren. In der Experimentalbedingung mit aktivierter Mobilisationsfunktion wurde ebenfalls ein Anstieg der Ermüdung beobachtet, jedoch war die Alpha-Spindel-Rate in allen drei Fahrtintervallen signifikant niedriger als in der Kontrollbedingung. Dies deutet darauf hin, dass die Mobilisation die Aufmerksamkeit der Fahrenden aufrechterhalten konnte – möglicherweise durch eine Stabilisierung des zerebralen Blutflusses. Ding et al. (2024) zeigen, dass kognitive Ermüdung die körperliche Leistungsfähigkeit beeinträchtigen kann. Umgekehrt ist bislang wenig darüber bekannt, wie sich körperliche Aktivität auf kognitive Ermüdung auswirkt (Xu et al., 2018). Die vorliegenden Ergebnisse legen nahe, dass die durch die Mobilisation induzierte Bewegungsaktivität (vgl. Kapitel 5.1) keinen negativen Einfluss auf die Vigilanz hatte. Vor dem Hintergrund der niedrigeren Alpha-Spindel-Rate stellt sich die Frage, ob sich dieser Effekt auch in den objektiven Leistungsmaßen widerspiegelt. Während die EEG-Daten deutliche Unterschiede zwischen den Bedingungen zeigten, unterschieden sich die Reaktionszeiten nicht signifikant. Da diese vor und nach der Versuchsfahrt erhoben wurden, ist es möglich, dass die während der Fahrt induzierte Ermüdung durch Erleichterung oder Aktivierung am Ende der Fahrt überlagert wurde (Schmidt et al., 2009). Zudem erforderte der Start des Reaktionstests eine Interaktion mit den Versuchsleiterinnen, was ebenfalls aktivierend gewirkt haben könnte. Für zukünftige Studien wäre der Einsatz einer automatisierten, auditiven Reaktionszeitaufgabe während der Fahrt denkbar. Allerdings könnte dies die Monotonie der Fahrsituation reduzieren und damit die Ermüdung abschwächen. Aus diesem Grund wurde in der vorliegenden Studie bewusst auf eine solche Maßnahme verzichtet. Die subjektiven Befragungen zeigten während der Fahrt einen deutlichen Anstieg von Ermüdung und Monotonie, was die erfolgreiche Induktion passiver Fahrerermüdung im gewählten Versuchsdesign bestätigt. Die erwartete Wirkung der Mobilisation ließ sich subjektiv jedoch nicht nachweisen. Möglicherweise waren die verwendeten Skalen zu grob, um Unterschiede zwischen den Bedingungen adäquat abzubilden. Zudem können Wiederholungseffekte und die begrenzte Validität subjektiver Angaben die Aussagekraft einschränken (Tversky & Kahneman, 1974). Subjektive Einschätzungen des eigenen Aufmerksamkeitsniveaus weichen häufig von objektiven Messwerten ab (Schmidt et al., 2009). Daher sollte den objektiven physiologischen Messungen bei der Interpretation der Ergebnisse mehr Gewicht beigemessen werden.

Zur Untersuchung möglicher Effekte eines sitzintegrierten Mobilisationssystems wurden auf der Basis bestehender Literatur relevante biomechanische, physiologische und subjektive Parameter ausgewählt, die in direktem Zusammenhang mit Rückenschmerzen (LBP) und Verkehrssicherheit stehen. Die Erhebung dieser Parameter erfolgte während oder unmittelbar vor bzw. nach der Fahrt. Dadurch

konnten keine Aussagen über langfristige Auswirkungen auf das Muskel-Skelett-System oder die Daueraufmerksamkeit getroffen werden. Die Ergebnisse deuten jedoch darauf hin, dass das Mobilisationssystem das Auftreten von Diskomfort verringert. Um die langfristige Wirksamkeit – insbesondere hinsichtlich der Entwicklung von LBP – zu evaluieren, wären Feldstudien mit längerer Beobachtungsdauer notwendig. Diese könnten auch zusätzliche Risikofaktoren wie Ganzkörpervibrationen, das Heben schwerer Lasten oder psychologische Belastungen (z. B. geringe Arbeitszufriedenheit) berücksichtigen.

Die kumulative Dissertation konzentrierte sich ausschließlich auf die Auswirkungen der Mobilisation bei lang andauernden monotonen Fahrten. Zukünftige Forschung sollte daher untersuchen, ob die sitzintegrierte Mobilisation nicht nur präventiv wirkt, sondern auch zur Linderung bestehender Beschwerden im unteren Rücken beitragen kann. Dies würde das Einsatzspektrum des Systems erweitern – von einer rein präventiven Maßnahme hin zu einer potenziellen therapeutischen Intervention im beruflichen Alltag.

Die hier vorliegenden Untersuchungen wurden als Fahrsimulator- und Realfahrstudie umgesetzt. Sowohl bei der simulierten als auch bei der realen Fahrt resultierten gewisse Einschränkungen aus der angewandten Methodik. Aufgrund der besseren Vergleichbarkeit und der verschiedenen Messtechniken, die noch nicht im realen Fahrzeug erprobt wurden, wurde die Studie zur Untersuchung der physiologischen Beanspruchung im Fahrsimulator durchgeführt (vgl. Kapitel 5.1 und Kapitel 5.2). Im Gegensatz zu einer realen Fahrt fehlen im statischen Fahrsimulator Vibrationen, die durch Unebenheiten der Straße verursacht werden. Bisherige Forschung hat gezeigt, dass Ganzkörpervibrationen das Auftreten eines Diskomfortempfindens erheblich steigern können (Du et al., 2018; Mansfield et al., 2017). Außerdem deuten die Erkenntnisse von Maikala und Bhambhani (2013) darauf hin, dass die Sauerstoffversorgung und das Blutvolumen des M. erector spinae durch Ganzkörpervibrationen beeinträchtigt werden, was zur Ermüdung der Muskulatur führen kann. Langes Sitzen in Verbindung mit Ganzkörpervibrationen vervielfacht das Risiko für Rückenschmerzen (Holzgreve et al., 2022; Lis et al., 2007; Miyamoto et al., 2000). Vorangegangene Studien von Balasubramanian und Adalarasu (2007) und Durkin et al. (2006) konnten eine Ermüdung der Muskulatur jedoch auch im statischen Fahrsimulator feststellen, weshalb die Durchführung der vorliegenden Studie im Fahrsimulator (vgl. Kapitel 5.1 und Kapitel 5.2) als ausreichend eingestuft wurde. Die Studie zur Untersuchung der passiven aufgabenbezogenen Ermüdung (vgl. Kapitel 5.3) wurde zur Standardisierung und Kontrollierbarkeit der Verkehrssituation auf einem Testgelände durchgeführt. Durch die abwechslungsreiche Topografie der Strecke entsprachen die Rahmenbedingungen nicht exakt denen auf einer typischen europäischen Autobahn. Um die für das Paradigma notwendige Monotonie zu erzeugen, wurde die vorgegebene Geschwindigkeit der Kolonnenfahrt auf konstant 35 km/h beschränkt. Die Ergebnisse der Studie zeigen, dass durch die Monotonie ein Vigilanzdekrement erzeugt

wurde. Jedoch schränken die untypische Fahrgeschwindigkeit und die Topografie der Versuchsstrecke die Validität der Studie geringfügig ein. Des Weiteren wurde die Fahrdauer von der gesetzlichen maximal möglichen ununterbrochenen Lenkzeit von viereinhalb Stunden auf zwei Stunden reduziert. Die Ergebnisse zeigen eine ausreichend starke Ermüdung der Versuchspersonen innerhalb dieser zwei Stunden. Außerdem bestätigte das subjektive Feedback im Falle einer längeren Fahrdauer ein erhöhtes Risiko für ermüdungsbedingte Abbrüche oder sogar Unfälle. Daher ergab sich für die vorliegende Studie eine maximale ethisch vertretbare Versuchsdauer von zwei Stunden. Diese Versuchsdauer reichte jedoch aus, um signifikante Unterschiede zwischen den Versuchsbedingungen festzustellen.

Die Generalisierbarkeit der Ergebnisse beider Studien auf Frauen kann kritisch gesehen werden. Da der Anteil der Männer in der Berufsgruppe laut dem Bundesamt für Güterverkehr (2019) bei 98% liegt, nahmen ausschließlich männliche Versuchspersonen an den Versuchen teil. Um einen Geschlechterunterschied hinsichtlich der Wirksamkeit der sitzintegrierten Mobilisationsfunktion gänzlich auszuschließen, wäre eine Replikation der Studien mit weiblichen und männlichen Versuchspersonen notwendig. An den vorliegenden Fahrsimulator- und Realfahrtstudien nahmen ausschließlich Personen teil, die Erfahrung im Führen eines Lkws vorweisen konnten. Eine Generalisierbarkeit der Ergebnisse auf die Berufsgruppe der Berufskraftfahrenden, einschließlich Busfahrenden, ist als unkritisch zu sehen, da sie einem ähnlichen Arbeitsumfeld mit vergleichbaren Fahraufgaben ausgesetzt sind (Crizzle et al., 2017).

Langes Sitzen ist ein allgegenwärtiges Phänomen in modernen Gesellschaften, insbesondere im beruflichen Kontext, während des Pendelns zwischen Zuhause und Arbeitsplatz sowie in der Freizeit z.B. bei der Nutzung digitaler Medien (Homer et al., 2019). So stellt langes Sitzen nicht nur bei Berufskraftfahrenden ein erhöhtes Gesundheitsrisiko dar, sondern in der gesamten Gesellschaft (Jia, 2021). LBP ist weltweit die Hauptursache für Fehlzeiten am Arbeitsplatz (Wu et al., 2020). Daher können die Erkenntnisse aus den hier vorliegenden Studien nicht nur im Lkw Anwendung finden, sondern zum Beispiel auch in anderen Fahrzeugtypen oder im Büro. Neben büro-spezifischen Gegenmaßnahmen zur Reduzierung der physiologischen Beanspruchung, z.B. der Unterbrechung der Sitzdauer durch Geh- oder Stehpausen, könnte die Mobilisationsfunktion zusätzlich positive Effekte erzielen.

Für die Integration einer Mobilisationsfunktion im Nutzfahrzeugbereich wäre denkbar, dass sich der Bund durch das Vorweisen des wissenschaftlichen Wirksamkeitsnachweises an einer finanziellen Förderung beim Kauf eines solchen Sitzes beteiligt. Auch bei der Kaufentscheidung der Transportunternehmen kann der objektive Wirksamkeitsnachweis bei der Rechtfertigung des Mehrpreises eine wesentliche Rolle spielen. Neben der Evaluation der objektiven Wirksamkeit ist jedoch auch das subjektive Diskomfortempfinden von hoher Bedeutung. Die sitzintegrierte Intervention hat das

Potenzial, den Beruf des Berufskraftfahrenden spürbar attraktiver zu gestalten, was zur einfacheren Rekrutierung von Nachwuchskräften beitragen könnte.

Die Ergebnisse der vorliegenden Arbeiten untermauern, dass die subjektive Einschätzung der Aufmerksamkeit der fahrenden Person nicht unbedingt mit objektiven Messungen übereinstimmt (Schmidt et al., 2009). Daher empfiehlt es sich, die Aktivierung des Mobilisierungssystems mit einem durch künstliche Intelligenz gesteuerten Aufmerksamkeitserkennungssystem zu verbinden. Das System könnte den Insassen vorschlagen, den Mobilisierungssitz zu aktivieren, sobald ein kritisches Vigilanzdekrement festgestellt wird. Bogler et al. (2014) zeigten, dass Signale aus der Nahinfrarotspektroskopie (NIRS) an der Oberfläche des menschlichen Gehirns mit der Vigilanz korrelieren. Jedoch reicht die Genauigkeit der NIRS-Methode zur kontinuierlichen Vigilanzfassung nach Bogler et al. (2014) noch nicht aus. Daher ist die Erfassung der Vigilanz während der Fahrt mithilfe mehrerer Vigilanzparameter denkbar. Neben der Vigilanz könnten auch weitere Parameter zur Erfassung der physiologischen Beanspruchung der fahrenden Person während der Fahrt erfasst werden, um die sitzintegrierte Mobilisation intelligent einzubinden. So könnte bei einer geringen Bewegungsaktivität, vermehrten Umsetzbewegungen oder einer ansteigenden Muskelsteifigkeit die Aktivierung der sitzintegrierten Mobilisation vorgeschlagen werden. Zudem könnten Gamifizierungsansätze zur Motivation für die Aktivierung der Mobilisation Anwendung finden. Dadurch besteht die Chance, dass das System häufiger aktiviert werden würde als ohne intelligente Einbindung, was zur Verbesserung der Gesundheit und Sicherheit im Straßenverkehr beitragen könnte.

Während in der Automobilindustrie Systeme zur sitzintegrierten Massage bzw. Mobilisierung von Insassen teilweise auf ihre Wirksamkeit zur Reduktion von Diskomfort und LBP sowie zum Erhalt der Vigilanz untersucht wurden, ist die Forschungslage im Fernverkehrsbereich gering. Bisher wurde im Nutzfahrzeugbereich der Langlebigkeit und der funktionalen Effizienz der Fahrersitze hohe Priorität eingeräumt. Aufgrund der physiologischen und kognitiven Beanspruchung von Berufskraftfahrenden besteht jedoch Handlungsbedarf, Nutzfahrzeugfahrersitze auf ihre Wirksamkeit auch in gesundheitlicher und verkehrssicherheitstechnischer Hinsicht zu evaluieren.

Das lange ununterbrochene Sitzen, dem Berufskraftfahrende regelmäßig ausgesetzt sind, erhöht nachweislich das Risiko für verschiedene Erkrankungen. Darüber hinaus kann exzessives Sitzen negative Auswirkungen auf die Aufmerksamkeit mit sich bringen. Neben dem vielversprechenden Potenzial der Automatisierung, birgt es das Risiko, Ermüdung zu fördern. Berufskraftfahrende ermüden in teilautomatisierten Fahrsituationen wesentlich stärker als bei einem aktiven Ausüben der Fahrtätigkeit. Bis zur vollständigen Automatisierung wird der Mensch die technischen Systeme überwachen und in kritischen Situationen die Steuerung des Fahrzeugs übernehmen müssen. Um eine kurze Übernahmedauer sowie eine adäquate Reaktion der Berufskraftfahrenden zu gewährleisten,

müssen entsprechende Präventionsmaßnahmen gegen die Ermüdung implementiert werden. Eine effektive Maßnahme zur Minimierung der kognitiven Ermüdung, aber auch der physiologischen Beanspruchung stellt die Unterbrechung der Fahrt dar. Jedoch hindern der zunehmende Zeitdruck und fehlende Parkplätze Berufskraftfahrende oft daran, ausreichend Pausen in ihren Arbeitsalltag zu integrieren. Daher bedarf es Maßnahmen, welche die physiologische Beanspruchung und die passive aufgabenbezogene Ermüdung von Berufskraftfahrenden während der Fahrt minimieren.

Zusammenfassend lässt sich festhalten, dass die Aufmerksamkeit der Berufskraftfahrenden durch die sitzintegrierte Mobilisation, während einer monotonen, teilautomatisierten zweistündigen Fahrt, aufrechterhalten werden konnte. Darüber hinaus zeigten sich während der viereinhalbstündigen simulierten Fahrt positive Effekte auf Bewegungsaktivität, Diskomfort und Muskelsteifigkeit. Der Sitz wirkt somit sowohl auf kognitiver als auch auf physiologischer Ebene. Ein möglicher gemeinsamer Wirkmechanismus könnte in der verbesserten Durchblutung liegen. Die Mobilisation könnte demnach das Potenzial haben, einer Minderdurchblutung sowohl der Rückenmuskulatur als auch des Gehirns entgegenzuwirken – ein vielversprechender Ansatzpunkt für zukünftige Forschung und die Weiterentwicklung ergonomischer Fahrzeugsitze.

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