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Review article

# Benchmarking occupational exoskeletons: An evidence mapping systematic review

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ABSTRACT

*Objectives:* To provide an overview of protocols assessing the effect of occupational exoskeletons on users and to formulate recommendations towards a literature-based assessment framework to benchmark the effect of occupational exoskeletons on the user.

*Methods:* PubMed (MEDLINE), Web of Science database and Scopus were searched (March 2, 2021). Studies were included if they investigated the effect of one or more occupational exoskeletons on the user.

*Results:* In total, 139 eligible studies were identified, encompassing 33, 25 and 18 unique back, shoulder and other exoskeletons, respectively. Device validation was most frequently conducted using controlled tasks while collecting muscle activity and biomechanical data. As the exoskeleton concept matures, tasks became more applied and the experimental design more representative. With that change towards realistic testing environments came a trade-off with experimental control, and user experience data became more valuable.

*Discussion:* This evidence mapping systematic review reveals that the assessment of occupational exoskeletons is a dynamic process, and provides literature-based assessment recommendations. The homogeneity and repeatability of future exoskeleton assessment experiments will increase following these recommendations. The current review recognises the value of variability in evaluation protocols in order to obtain an overall overview of the effect of exoskeletons on the users, but the presented framework strives to facilitate benchmarking the effect of occupational exoskeletons on the users across this variety of assessment protocols.

## 1. Introduction

Occupational exoskeletons are a topic of wide interest within the domains of injury prevention, ergonomics and workforce enabling technologies (Torricelli et al., 2020; de Looze et al., 2016). This is because many occupational workers are at a high risk of work-related musculoskeletal disorders due to their exposure to excessive repetitive tasks, non-neutral and highly repetitive postural deviations and heavy lifting (Da Costa and Vieira, 2010). Forty percent of European workers still suffer from low back, shoulder or neck pain (Parent-Thirion et al., 2019). In construction workers for example, a meta-analysis states that low back pain has a one-year prevalence of 51% (Umer et al., 2018). Additionally, ageing of the workforce emphasises the growing need for (i) prevention of work-related disorders, (ii) a reduction in the impairment of work due to these disorders, (iii) better support for disabled workers, and (iv) the promotion of work ability (Ilmarinen, 2006;

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Meucci et al., 2015). Occupational exoskeletons could play a key role in achieving these objectives. An occupational exoskeleton is a device designed to wear on the body and to support workers in an occupational setting to perform physically demanding activities (de Looze et al., 2016; Young and Ferris, 2017; Fisahn et al., 2016; Lee et al., 2012a). Exoskeleton designers aim to develop devices that are capable of smoothly interacting with the user along the whole work space by enhancing human well-being and optimising overall system performance, and without hindering natural kinematics or causing discomfort or injury (D'Elia et al., 2017). Since work-related musculoskeletal disorders and fatigue are frequently occurring in the lower back and the shoulder joint (Umer et al., 2018; Hussain, 2004; Afonso et al., 2014; Fouquet et al., 2015; Wixted et al., 2018; Claus et al., 2019; Lima et al., 2019), occupational exoskeletons most often target these body parts. Back exoskeletons aim to reduce the load on the lower lumbar spine by providing an assistive torque around the hips and lower spine. Shoulder exoskeletons are specifically designed for prolonged or repetitive arm elevation, supporting the upper arm when working at or above shoulder level. Furthermore, three categories of exoskeletons can be distinguished based on the nature of the assistance the device provides. Active exoskeletons are equipped with one or more actuators such as electric motors, hydraulic actuators or pneumatic muscles, which actively aid the wearer by adding energy to the system (de Looze et al., 2016; Lee et al., 2012a; Gopura et al., 2011). Passive exoskeletons use deformation of springs or other elastic materials to store and return energy to support the human posture or motion without energy injection from external sources into the coupled human-machine system (de Looze et al., 2016; Lee et al., 2012a). A third category is quasi-passive exoskeletons, where the characteristics of a spring based actuation system are modified by an active actuator (Grazi et al., 2020). The effect of an exoskeleton on the user is ideally assessed by large sample prospective, long-term studies. However, before considering such experiments, more data supporting the use of exoskeletons is required (Torricelli et al., 2020), and their ability to cope with health and safety constraints needs to be established first (Torricelli et al., 2020; Gopura et al., 2016; Bogue, 2018; McFarland and Fischer, 2019). Therefore, exoskeleton assessments currently often focus on the effect of an exoskeleton on risk factors for developing musculoskeletal disorders, working performance, effort or experience [e.g. 23, 24, 25, 26]. As a result, Torricelli and colleagues proposed investigating an exoskeleton's functional performance and user experience during a benchmarking process (Torricelli et al., 2020). Functional performance includes technical, biomechanical and physiological indicators, and user experience takes perceptual, emotional, and cognitive aspects into account. The combination of these outcomes may provide further insights in the effect of exoskeletons on health and safety (Keyserling). Although Torricelli et al. suggested a common benchmarking ecosystem (Torricelli et al., 2020), a well-defined framework is still lacking and therefore, exoskeleton assessments are differently approached in each study. Additionally, occupational exoskeletons target multiple occupational sectors. The combination of these aspects leads to a vast set of assessment protocols and parameters. This was reflected in the recent review of Pesenti and colleagues, who reported that comparison of the effect of different occupational back exoskeletons was obstructed by the large variability of assessment protocols (Pesenti et al., 2021). Despite ongoing efforts (Torricelli et al., 2020; Lee et al., 2012a; Bostelman et al., 2017), a framework for benchmarking the effect of occupational exoskeletons is still lacking to date. Such framework would provide the tailored feedback developers need to optimise the development cycle and accelerate the road to market introduction. End-users, on the other side, would benefit from such framework since it would expedite finding out which solution optimally fulfils the requirements of a specific occupational setting. Occupational exoskeletons could increase the quality of life of the work force, but an assessment framework for benchmarking to benchmark the effect of these devices is lacking. Perhaps resulting from this lack, reported assessments have used a wide range of approaches, impeding researchers and practitioners to keep an overview and compare different exoskeletons among studies. Indirectly, the lack of an assessment framework is also hampering field implementation and improvements in the efficiency of the lab-to-market cycle. Therefore, the purpose of this evidence mapping systematic review is to provide an overview of the literature concerning occupational exoskeleton assessment and to use the gathered data to propose a literature-based framework for future occupational exoskeleton benchmarking.

## 2. Methods

The review protocol was developed and the systematic review was conducted with respect to the *Preferred Reporting Items for Systematic review and Meta-analyses* (PRISMA) guidelines (Page et al., 2021). Although an a priori protocol was developed, this review did not fit the *International Prospective Register of Systematic Reviews* (PROSPERO) format, and subsequently no registration of this review was completed. To construct the research question and determine the eligibility criteria, the PICOS (Population, Intervention, Control, Outcome, Study design) approach was used (Moher et al., 2015).

### 2.1. Eligibility criteria

Studies were deemed eligible if they investigated the effect of an occupational exoskeleton on the users through user-centred, non-mechanical, parameters. Papers only reporting mechanical outcomes were excluded. No constraints were imposed on age or sex of participants (P), but studies investigating animals, cadavers or people with non-work-related injuries in the last 6 months were excluded. In the latter group, an exception was made for participants suffering from work-related musculoskeletal disorders. Interventions (I) were considered eligible when the use of an occupational exoskeleton was included. Tool supporting devices or apparatus with an external arm were excluded. All user-centred parameters were deemed eligible outcomes (O),. Papers only reporting mechanical responses of the exoskeleton, rather than of the user, were excluded.

### 2.2. Information sources and search strategy

The Pubmed (MEDLINE), Web of Science (WoS) and Scopus databases were searched for relevant articles. The last search in all databases was performed on March 2, 2021. The search strategy was developed by two researchers (S.D.B. and B.T.) using the participant and intervention component of the PICOS approach. Specific comparison, outcome or study design criteria were not defined in order to include the entire range of exoskeleton assessments and the exclusion of rehabilitation exoskeletons was specified in the search strategy. The complete search strategies of the databases can be found in Table 1.

**Table 1**
Search strategy for the databases that were included in this systematic review.

| Database | Search strategy | Hits |
|---|---|---|
| Pubmed (MEDLINE) | “humans”[MeSH Terms] AND (“exoskeleton”[All Fields] OR “assistive device”[all fields] OR “exoskeletal”[All Fields] OR “exosuit”[All Fields]) NOT “rehabilitation”[MeSH] | 1417 |
| Web of Science | TS=((“exoskeleton” OR “assistive device” OR “exoskeletal” OR “exosuit”) AND “human” NOT “rehabilitation”) | 1754 |
| Scopus | TITLE-ABS-KEY((“human*’’) AND ((“exoskeleton*’’) OR (“Assistive device*’’) OR (“exoskeletal”) OR (“exosuit”)) AND ((“assess*’’) OR (“evaluate*’’)) AND NOT (“rehabilitation”) AND NOT (“animal*’’)) | 1772 |

### 2.3. Study selection and risk of bias assessment

One author (S.D.B.) performed the database search and retrieved all titles, abstracts, full texts and citations. Subsequently, duplicates were removed and the studies were imported into the Rayyan web application (https://rayyan.qcri.org) (Ouzzani et al., 2016), where four reviewers (S.D.B., J.Gh., J.Ge. and K.D.P.) screened the articles on titles and abstracts for eligibility, and eventually reviewed the remaining full texts independently. Disagreements were resolved through discussion. References lists and citations of all included articles were checked, to ensure no eligible articles were missed.

Two reviewers (S.D.B. and R.G.) independently assessed the studies' risk of bias with the Revised Cochrane Risk of Bias tool for crossover trials (RoB 2.0) (Higgins et al., 2019). Each of the five domains of the RoB 2.0 tool was rated using the provided signalling questions. Based on these domain assessments, an overall risk of bias judgement was made per study. The guidelines formulated by the Cochrane community were followed and disagreements were settled through discussion and consensus.

### 2.4. Data extraction and synthesis

A detailed inventory of the exoskeletons and assessment protocols was constructed during full-text screening. Missing data was not pursued in any form and were added to the risk of bias assessment if relevant. Studies were categorised by the supported body part and by the type of exoskeleton assessment. In the latter, 3 assessment categories were distinguished, i.e. validation, evaluation and field studies (Table 2). Studies in a controlled environment without clear link to occupational work, were defined as validation studies. When tasks in a controlled environment contained a link with occupational work, the study was called an evaluation study. Exoskeleton assessments performed in a real occupational setting were classified as field studies. Disagreements were solved through discussion and consensus.

## 3. Results

### 3.1. Study selection

The combined search strategy yielded 4943 articles, of which 4222 unique studies remained following duplicate exclusion. After full-text screening, 139 studies were included in this systematic review. The complete study selection process is presented in the PRISMA chart (Fig. 1). The earliest studies in this review were published in 2005 and from 2015 on, the amount of eligible studies increased fast (Fig. 2). In 2019 and 2020, 36 and 38 included papers were published, respectively. The included papers comprised 51 validation studies (Aida et al., 2009; Blanco et al., 2019; De Busk et al., 2017; de Vries et al., 2019; Ebrahimi et al., 2017; Han et al., 2019, 2020; Hao et al., 2020; Hondzinski et al., 2019; Hull et al., 2020; Huysamen et al., 2018a; Inose et al., 2017; Inoue and Noritsugu, 2018; Jeong et al., 2020; Johnson et al., 2018; Kazerooni et al., 2019; Kim et al., 2015, 2020a,a; Kobayashi and Nozaki, 2008; Koopman et al., 2019b; Kosaki and Li, 2020; Kudernatsch and Peterson, 2018; Kurita et al., 2017; Lamers et al., 2020; Lanotte et al., 2018; Lazzaroni et al., 2019; Lee et al., 2012b; Li et al., 2013; Lim et al., 2015; Lotti et al., 2020; Luo and Yu, 2013; Muramatsu et al., 2013; Näf et al., 2018; Naruse et al., 2005; Natividad et al., 2019; Otten et al., 2018; Park and Cho, 2017; Sasaki and Takaiwa, 2014; Shin et al., 2019; Sylla et al., 2014a,b; Tiseni et al., 2019; Ulrey and Fathallah, 2013; Wehner et al., 2009; Wijegunawardana et al., 2019; Yong et al., 2017; Yu et al., 2019; Chen et al., 2018; Zhang et al., 2016), 66 evaluation studies (Abdoli-E et al., 2006; Abdoli-E and Stevenson, 2008; Abdoli-Eramaki et al., 2007; Alabdulkarim et al., 2019; Alabdulkarim and Nussbaum, 2019; Alemi et al., 2019, 2020, Baltrusch et al., 2018, 2019, 2020a,b; Bosch et al., 2016; Bridger et al., 2018; Daratany and Taveira, 2020; Frost et al., 2009; Gilotta et al., 2018; Godwin et al., 2009; Gorsic et al., 2020; Grazi et al., 2020; Huysamen et al., 2018b; Hyun et al., 2019, 2020; Ji et al., 2020; Kelson et al., 2019; Kim et al., 2020b,c; Kim and Nussbaum, 2019; Kinne et al., 2020; Ko et al., 2018; Koopman et al., 2019b, 2020; Kozinc et al., 2020a; Lamers et al., 2018; Lee and Chee, 2013; Lotz et al., 2009; Luger et al., 2019; Madinei et al., 2020a,b; Maurice et al., 2020; Miura et al., 2018b; Muramatsu et al., 2011; Pacifico et al., 2020; Picchiotti et al., 2019; Pillai et al., 2020; Pinho et al., 2020; Qu et al., 2021; Sadler et al., 2011; Schmalz et al., 2019; So et al., 2020; Spada et al., 2017, 2019; Steinhilber et al., 2020; Theurel et al., 2018; Toxiri et al., 2018; Van Engelhoven et al., 2019; von Glinski et al., 2019; Wei et al., 2020a,b; Whitfield et al., 2014; Xiloyannis et al., 2019; Yin et al., 2019, 2020; Yong et al., 2019; Zhu et al., 2018; Poliero et al., 2020; Tan et al., 2019) and 22 field studies (Amandels et al., 2019; Baltrusch et al., 2021; Claramunt et al., 2019; De Bock et al., 2021; de Vries et al., 2021; Dewi and Komatsuzaki, 2018; Ferreira et al., 2020; Gillette and Stephenson, 2018; Gillette and Stephenson, 2019; Graham et al., 2009; Hefferle et al., 2020; Hensel and Keil, 2019; Iranzo et al., 2020; Miura et al., 2018b; Motmans et al., 2019; Moyon et al., 2018; Omoniyi et al., 2020; Settembre et al., 2020; Smets, 2019; Spada et al., 2018; Thamsuwan et al., 2020; Wang et al., 2021).

**Table 2**
This evidence mapping systematic review proposes three exoskeleton assessment categories; validation, evaluation and field assessment.

| Assessment | Description | Criteria |
|---|---|---|
| Validation | Verify effect of a new concept. Often used in proof-of-concept studies. Requires a highly controlled environment. Facilitates rapid prototyping | Tasks in controlled environment without link to occupational work |
| Evaluation | Investigate effect of exoskeleton on the user. Controlled, yet applied environment. Statistical power. | Tasks in controlled environment with link to occupational work |
| Field | Highly uncontrolled environment. Only for more mature devices. | Assessments in real occupational setting |

### 3.2. Risk of bias assessment

The two authors assessing the risk of bias agreed in 89.2% of the studies. The risk-of bias assessment revealed high risk of bias for 135 included studies. Four studies were judged as having some concerns of bias (Hull et al., 2020; Luger et al., 2019; Madinei et al., 2020a; So et al., 2020). Inadequate blinding, limited randomisation and the use of patient-reported outcome measures were the main determinants for the high risk of bias (Fig. 3). A detailed overview of the risk assessment is available in appendix Table A.1.

### 3.3. Exoskeletons

In total, 73 different exoskeletons were evaluated in the included studies. Thirty-seven active, 35 passive and 1 quasi-passive exoskeletons were included. Within those 73 devices, 32 back, 23 shoulder, 9 lower limb, 4 full body and 3 elbow exoskeletons were distinguished. Additionally, 2 devices supported the entire upper limb. The lower limb, full body, elbow and upper limb exoskeletons were categorised as other exoskeletons for the remainder of this review. Fig. 4 illustrates the distribution of validation, evaluation and field studies per exoskeleton.

### 3.4. Participant characteristics

Table 3 represents an overview of the study samples for each assessment and exoskeleton category. In total, 1601 participants (age: 30.1 ± 7.5 year, body mass: 73.4 ± 9.8 kg, height: 1.76 ± 0.05 m) were subjected to an exoskeleton evaluation. The average ratio of male:female participants was 5:1 (no sex was mentioned for 260 participants). Additionally, 19% of the studies recruited occupational workers to

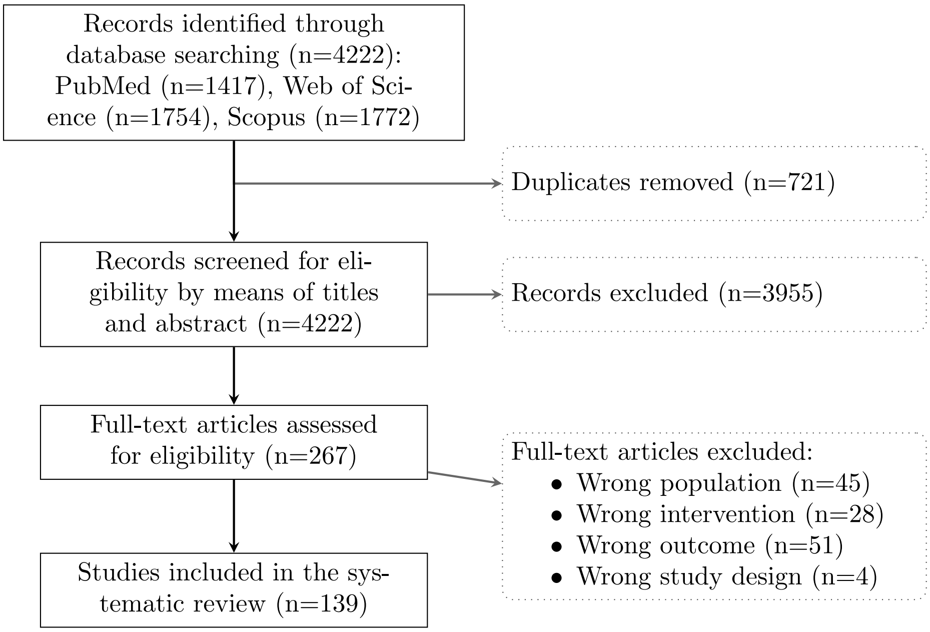

**Fig. 1.** Selection process for research articles (n = 139) included in this systematic review. Adapted version of the recommendations in the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Page et al., 2021).

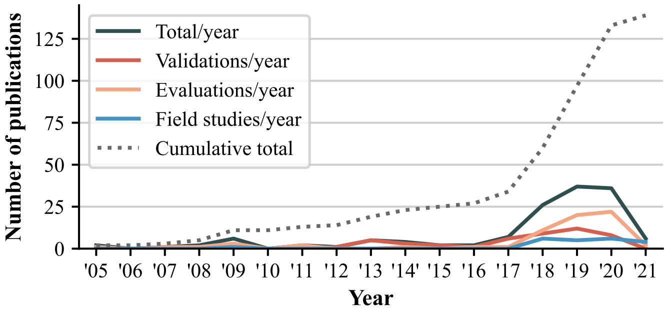

**Fig. 2.** The number of included publications in total and per category were illustrated from 2005 to 2021.

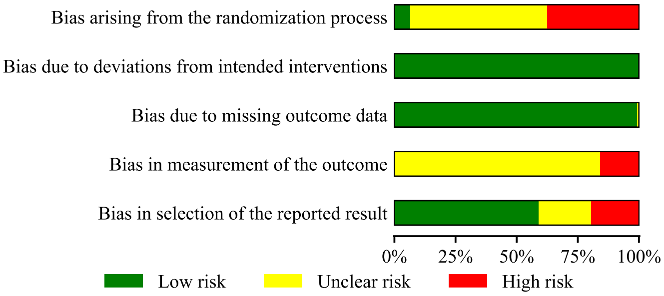

**Fig. 3.** Risk of bias across all included studies.

participate in the experiment (N = 404, age: 41.0 ± 6.3 year, body mass: 80.0 ± 6.7 kg, height: 1.75 ± 0.05 m). In the other studies, a convenience sample was used or the background of the participants was not specified (N = 1197, age: 27.0 ± 4.1 year, body mass: 72.7 ± 6.5 kg, height: 1.76 ± 0.05 m).

### 3.5. *Overview of tasks*

#### 3.5.1. *Back exoskeletons*

*3.5.1.1. Validation assessment.* Out of the 21 back exoskeleton validation studies (Chen et al., 2018; De Busk et al., 2017; Han et al., 2020; Inose et al., 2017; Johnson et al., 2018; Kazerooni et al., 2019; Kobayashi and Nozaki, 2008; Koopman et al., 2019a; Lamers et al., 2020; Lanotte et al., 2018; Lazzaroni et al., 2019; Li et al., 2013; Muramatsu et al., 2013; Näf et al., 2018; Naruse et al., 2005; Shin et al., 2019; Ulrey and Fathallah, 2013; Wehner et al., 2009; Yong et al., 2017; Zhang et al., 2016), 7 studies included an isometric task with an inclined trunk (Kobayashi and Nozaki, 2008; Koopman et al., 2019a; Lamers et al., 2020; Li et al., 2013; Luo and Yu, 2013; Ulrey and Fathallah, 2013; Zhang et al., 2016). Six of those 7 studies included a condition without additional weights (Kobayashi and Nozaki, 2008; Koopman et al., 2019a; Li et al., 2013; Luo and Yu, 2013; Ulrey and Fathallah, 2013; Zhang et al., 2016) and in 3 studies additional weights with masses between 4 and 16 kg were used (Kobayashi and Nozaki, 2008; Lamers et al., 2020; Ulrey and Fathallah, 2013). Trunk flexion angles or relative heights adjusted to the body dimensions of the participants were specified in 5 of the 7 studies to standardise the trunk flexion (Koopman et al., 2019a; Lamers et al., 2020; Li et al., 2013; Luo and Yu, 2013; Zhang et al., 2016). flexion angles ranged from 0 to 90°, where 60° was the most common, and the task duration varied from 4 s to 5 min.

Dynamic isolated lifting tasks, which were included in 12 back exoskeleton validation studies (Naruse et al., 2005; De Busk et al., 2017; Han et al., 2020; Johnson et al., 2018; Lanotte et al., 2018; Lazzaroni et al., 2019; Yong et al., 2017; Inose et al., 2017; Kazerooni et al., 2019; Muramatsu et al., 2013; Shin et al., 2019; Zhang et al., 2016), were most frequently used to assess the effectiveness of back exoskeletons. Seven studies used free lifting in their protocol, of which all 7 focused on symmetric lifting tasks (Naruse et al., 2003; De Busk et al., 2017; Han et al., 2020; Johnson et al., 2018; Lanotte et al., 2018; Lazzaroni et al., 2019; Yong et al., 2017). One study also included asymmetric lifting with 60°rotation (Naruse et al., 2003). In 5 studies, stoop lifting was performed with weights with masses between 0 and 15 kg (Inose et al., 2017; Kazerooni et al., 2019; Muramatsu et al., 2013; Shin et al., 2019; Zhang et al., 2016). When the number of repetitions was specified, 3 to

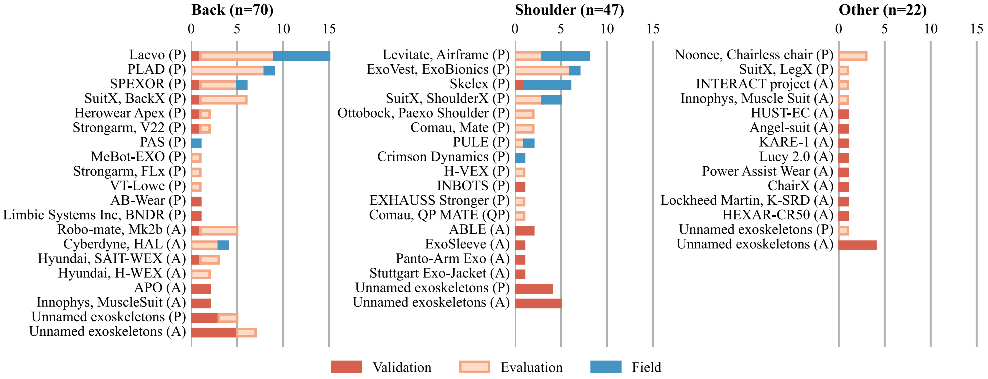

**Fig. 4.** The distribution of the exoskeleton assessment types was illustrated across different exoskeletons. Back, shoulder and other exoskeletons were distinguished. First passive devices (P) were listed, followed by active exoskeletons (A). Unnamed exoskeletons were listed at the bottom. The distribution was expressed as the absolute number of occurrences.

**Table 3**
This table provides an overview of the recruited participants in this review. N = number of studies, # = total number of participants, M = male participants, F = female participants, mean ($\bar{x}$) and standard deviation ($\sigma$) of the number of participants per study was calculated.

| Exoskeleton | Actuation | Assessment | N | # (M:F) | $\bar{x} \pm \sigma$ |
|---|---|---|---|---|---|
| **Back** | Passive | Validation | 10 | 65 (46 : 16) | 6.5 ± 5 |
| | | Evaluation | 27 | 419 (314 : 101) | 15.5 ± 7.6 |
| | | Field | 9 | 122 (103 : 10) | 13.6 ± 7.8 |
| | | Total | 46 | 606 (463 : 127) | 13.2 ± 7.9 |
| | Active | Validation | 11 | 31 (17 : 0) | 2.8 ± 2.4 |
| | | Evaluation | 13 | 152 (108 : 14) | 11.7 ± 3.7 |
| | | Field | 1 | 9 (9 : 0) | – |
| | | Total | 25 | 192 (134 : 14) | 7.7 ± 5.4 |
| | Total | | 71 | 798 (597 : 141) | 11.2 ± 7.5 |
| **Shoulder** | Passive | Validation | 6 | 49 (44 : 5) | 8.2 ± 3.5 |
| | | Evaluation | 18 | 271 (177 : 56) | 15.1 ± 7.3 |
| | | Field | 12 | 221 (123 : 10) | 18.4 ± 23.3 |
| | | Total | 36 | 541 (344 : 71) | 15.0 ± 14.5 |
| | Active | Validation | 10 | 50 (15 : 7) | 5.0 ± 4.1 |
| | | Evaluation | 1 | 10 (10 : 0) | – |
| | | Field | 0 | – | – |
| | | Total | 11 | 60 (25 : 7) | 5.0 ± 4.1 |
| | Total | | 47 | 601 (369 : 78) | 12.8 ± 13.4 |
| **Other** | Passive | Validation | 0 | – | 0 |
| | | Evaluation | 5 | 134 (120 : 2) | 26.8 ± 16.9 |
| | | Field | 0 | – | – |
| | | Total | 5 | 134 (120 : 2) | 26.8 ± 16.9 |
| | Active | Validation | 14 | 50 (24 : 2) | 3.6 ± 2.9 |
| | | Evaluation | 2 | 18 (8 : 0) | 9.0 ± 1.4 |
| | | Field | 0 | – | – |
| | | Total | 16 | 68 (32 : 2) | 4.3 ± 3.3 |
| | Total | | 21 | 202 (152 : 4) | 9.6 ± 12.7 |
| **Total** | | | 139 | 1601 (1118 : 223) | 11.5 ± 10.7 |

50 stoop lifts from ground level to hip height were executed during the validation (Shin et al., 2019; Zhang et al., 2016).

Three studies used functional tasks during the validation of a back exoskeleton (Näf et al., 2018; Johnson et al., 2018; Chen et al., 2018). Two studies investigated walking, sit-to stand and climbing stairs (Johnson et al., 2018; Chen et al., 2018). Naf et al. (Näf et al., 2018) used the functional task battery developed by Baltrusch and colleagues (Baltrusch et al., 2018).

*3.5.1.2. Evaluation assessment.* Isometric tasks with an inclined trunk were included in 7 of the 41 back exoskeleton evaluations (Bosch et al., 2016; Kim et al., 2020b; Madinei et al., 2020b; Koopman et al., 2020; Lamers et al., 2018; Wehner et al., 2009; Wei et al., 2020b). Six of the 7 evaluations included this isometric posture in the evaluation protocol without adding additional weight (Bosch et al., 2016; Kim et al., 2020b; Madinei et al., 2020b; Koopman et al., 2020; Wehner et al., 2009; Wei et al., 2020b). Two studies included additional weights with masses of 4.5 (Lamers et al., 2018) or 13.6 kg (Wehner et al., 2009). Three studies applied this static stooped posture during an assembly task, i.e. completing a grooved peg board assembly task (Bosch et al., 2016; Kim et al., 2020b; Madinei et al., 2020b). Trunk flexion angles ranged from 30° to 90° (Bosch et al., 2016; Lamers et al., 2018; Wehner et al., 2009; Wei et al., 2020b), where 50° was most common. During the assembly tasks, the working height was adjusted to anatomic landmarks, i.e. trochantor major, knee and ankle height.

Thirty-three back exoskeleton evaluations used a dynamic isolated lifting task (Abdoli-E et al., 2006; Abdoli-E and Stevenson, 2008; Abdoli-Eramaki et al., 2007; Alemi et al., 2019; Alemi et al., 2020; Baltrusch et al., 2019; Baltrusch et al., 2020a; Frost et al., 2009; Godwin et al., 2009; Gorsic et al., 2020; Huysamen et al., 2018c; Hyun et al., 2020; Ji et al., 2020; Kinne et al., 2020; Ko et al., 2018; Koopman et al., 2019b; Koopman et al., 2020; Kozinc et al., 2020a; Lamers et al., 2018; Lotz et al., 2009; Madinei et al., 2020a; Miura et al., 2018b; Picchiotti et al., 2019; Poliero et al., 2020; Qu et al., 2021; Sadler et al., 2011; Tan et al., 2019; Toxiri et al., 2018; von Glinski et al., 2019; Wei et al., 2020a; Whitfield et al., 2014; Yin et al., 2019; Yong et al., 2019). Twenty-one evaluation protocols encompassed a symmetric free lifting task (Abdoli-E and Stevenson, 2008; Abdoli-Eramaki et al., 2007; Alemi et al., 2019; Alemi et al., 2020; Baltrusch et al., 2019; Baltrusch et al., 2020a; Frost et al., 2009; Godwin et al., 2009; Gorsic et al., 2020; Huysamen et al., 2018c; Koopman et al., 2019b; Koopman et al., 2020; Kozinc et al., 2020a; Lamers et al., 2018; Lotz et al., 2009; Picchiotti et al., 2019; Poliero et al., 2020; Qu et al., 2021; Sadler et al., 2011; von Glinski et al., 2019; Wei et al., 2020a; Whitfield et al., 2014; Yin et al., 2019). Alemi et al. (2020) also investigated symmetric and asymmetric kneeled lifting. Fifteen studies included stoop lifting (Abdoli-E et al., 2006; Abdoli-Eramaki et al., 2007; Abdoli-Eramaki et al., 2007; Alemi et al., 2019; Frost et al., 2009; Hyun et al., 2020; Ji et al., 2020; Ko et al., 2018; Koopman et al., 2019b; Koopman et al., 2020; Kozinc et al., 2020a; Miura et al., 2018b; Tan et al., 2019; Toxiri et al., 2018; Yong et al., 2019), 9 squat lifting (Abdoli-E et al., 2006; Abdoli-E and Stevenson, 2008; Abdoli-Eramaki et al., 2007; Alemi et al., 2019; Frost et al., 2009; Koopman et al., 2019b; Koopman et al., 2020; Kozinc et al., 2020a; Lamers et al., 2018) and 2 semi-squat lifting (Hyun et al., 2020; Ko et al., 2018) during the exoskeleton evaluation. Another evaluation study utilised a customised palletising task where 64 boxes were moved from one euro-pallet to another (Kinne et al., 2020). The masses used in these tasks varied between 0 kg and 25 kg. In 7 studies the weights' masses were adjusted to a relative portion of the body mass or back extensor strength (Alemi et al., 2019; Godwin et al., 2009; Lotz et al., 2009; Madinei et al., 2020a; Qu et al., 2021; Sadler et al., 2011; Whitfield et al., 2014). In most studies participants were instructed to lift from the ground, ankle or mid-shin level to hip, table or waist height. The lifts were executed 1 up to 270 times, most often accompanied by lowering the weight in a separate movement. The lifting pace was not specified in all studies, but it ranged from 4 to 15 lifts per minute and the longest lifting trials lasted 45 min.

Functional tasks were included in 7 evaluation studies (Baltrusch et al., 2018; Baltrusch et al., 2019; Baltrusch et al., 2020b; Ko et al., 2018; Koopman et al., 2020; Gorsic et al., 2020; Poliero et al., 2020). Two studies used the functional task battery developed by Baltrusch and colleagues (Baltrusch et al., 2018; Baltrusch et al., 2020a). Three studies included walking (Baltrusch et al., 2019; Gorsic et al., 2020; Poliero et al., 2020). Less frequent functional tasks were a combined lifting and walking movement (Ko et al., 2018), a sit-to-stand task (Gorsic et al., 2020), a seated perturbation task (Gorsic et al., 2020), and range of motion tests (Koopman et al., 2020).

*3.5.1.3. Field assessment.* All 10 back exoskeleton assessments in the field included a customised task (Amandels et al., 2019; Baltrusch et al., 2020b; Dewi and Komatsuzaki, 2018; Graham et al., 2009; Hensel and Keil, 2019; Miura et al., 2018b; Motmans et al., 2019; Omoniyi et al., 2020; Settembre et al., 2020; Thamsuwan et al., 2020). These tasks were typical daily tasks of the industry of interest, such as farming (Omoniyi et al., 2020), luggage handling (Baltrusch et al., 2020b), logistics (Motmans et al., 2019), medical care (Settembre et al., 2020) or the manufacturing industry (Graham et al., 2009). Two studies also included symmetric and asymmetric free lifting tasks in which a weight with a mass of 2.7 kg was lifted from the ground until 0.75 m (Omoniyi et al., 2020; Thamsuwan et al., 2020).

### 3.5.2. Shoulder exoskeletons

*3.5.2.1. Validation assessment.* Seven out of the 16 shoulder validation studies implemented isometric shoulder work in the validation protocol to assess the functionality of a shoulder exoskeleton (de Vries et al., 2019; Hull et al., 2020; Huysamen et al., 2018a; Kim et al., 2018a; Kurita et al., 2017; Tiseni et al., 2019; Lee and Chee, 2013). Here, a variation of shoulder flexion angles was used, ranging from 30° up to 150°, where 90° of shoulder flexion was most frequently used. All 7 studies included a condition without additional weight. In three studies additional weights were used, with a median mass of 2 kg and a range from 0.5 to 14 kg (Huysamen et al., 2018a; Kim et al., 2018a; Kurita et al., 2017). The duration of these isometric tasks ranged from 4 s to 10 min and in one study the posture was maintained until exhaustion (Tiseni et al., 2019). Additionally, 2 studies included a quasi-isometric overhead screwing task (Sylla et al., 2014a; Sylla et al., 2014b).

Dynamic shoulder tasks were incorporated in 8 validation studies (Blanco et al., 2019; Ebrahimi et al., 2017; Hull et al., 2020; Inoue and Noritsugu, 2018; Kim et al., 2018a; Natividad et al., 2019; Park and Cho, 2017; Tiseni et al., 2019). In these movements started at 0° shoulder flexion and reached up to 90° (Blanco et al., 2019; Hull et al., 2020; Natividad et al., 2019; Tiseni et al., 2019), 100° (de Vries et al., 2019) or head height (Inoue and Noritsugu, 2018; Hull et al., 2020). Four studies used additional weights to execute the task, weights with a mass of 1.7, 2 or 7 kg were used (Blanco et al., 2019; Kim et al., 2018a; Park and Cho, 2017). Three validation studies included functional tasks, i.e. a range of motion task of the shoulder joint (Tiseni et al., 2019) and static postures with the arms at hip and elbow level (Inoue and Noritsugu, 2018; Kudernatsch and Peterson, 2018).

*3.5.2.2. Evaluation assessment.* Out of the 18 shoulder exoskeleton evaluations, 4 evaluation protocols contained an isometric posture with the shoulder in 90° flexion. The posture was maintained for 60 s without additional mass (Pacifico et al., 2020), or until exhaustion with a 3.5-kg weight (Gilotta et al., 2018; Spada et al., 2017; Spada et al., 2019).

In all 18 evaluation studies, a quasi-isometric task was included. Eleven studies simulated a drilling or screwing task at overhead height (Alabdulkarim et al., 2019; Grazi et al., 2020; Kim et al., 2018b; Kim et al., 2018c; Kim and Nussbaum, 2019; Pinho et al., 2020; Van Engelhoven et al., 2019; Yin et al., 2020), eye level (Alabdulkarim and Nussbaum, 2019; Schmalz et al., 2019) or shoulder height (Hyun et al., 2019; Kim et al., 2018b; Kim et al., 2018c; Kim and Nussbaum, 2019). The weight of the drill ranged from 0.45 to 5.9 kg with a median weight of 2.3 kg, two studies used no additional mass in the simulated task (Grazi et al., 2020; Schmalz et al., 2019). A simulated wiring task without additional mass was included in 3 studies (Kim et al., 2018b; Kim et al., 2018c; Kim and Nussbaum, 2019), in 1 study participants were instructed to move magnets on a metal plate (Daratany et al., 2020). The working height in all 4 studies was overhead or at shoulder height. In 4 studies a quasi-isometric precision task at shoulder height where a sinusoidal trace was followed with an extended arm without additional weight was included (Gilotta et al., 2018; Spada et al., 2017; Spada et al., 2019; Pacifico et al., 2020). When the duration was specified, it ranged between 30 s and 10 min. Other studies specified the amount of work that had to be completed.

Five evaluation studies investigated a dynamic lifting task (Gilotta et al., 2018; Pacifico et al., 2020; Spada et al., 2017; Spada et al., 2019; Theurel et al., 2018). In three studies participants were instructed to lift a 3.5-kg weight with extended elbows from hip to shoulder height with a lifting pace of 30 lifts per minute for 10 min or until exhaustion. Pacifico and colleagues (Pacifico et al., 2020) instructed isolated flexion extension in the shoulder up to 90° shoulder flexion without additional weight. Another study focused on lifting between knee and shoulder height and included task in which boxes were stacked from the ground until 1.40 m (Theurel et al., 2018). Here, the weights' masses were adjusted to the participants sex (M: 9 and 15 kg, F: 5 and 8 kg).

Two studies used functional tasks in the evaluation of the exoskeleton (Kim et al., 2018c; Theurel et al., 2018). One study investigated walking and donning and doffing of the exoskeleton (Kim et al., 2018c). In another study participants were instructed to walk with 15 kg for male participants and 8 kg for female participants (Theurel et al., 2018).

*3.5.2.3. Field assessment.* Three of the 12 shoulder exoskeleton field assessments included controlled tasks within the field assessment (De Bock et al., 2021; Spada et al., 2018; Wang et al., 2019). De Bock et al. (De Bock et al., 2021) instructed an isometric task with the arms horizontally positioned at shoulder height, a lifting task with extended arms from hip to shoulder height, a squatting task and a stoop lifting task. All tasks were executed with a 5-kg weight. Spada et al. (2018) investigated an isometric posture while holding a mass of 3.5 kg with the arms horizontally positioned at shoulder height, a lifting task from hip height to shoulder height with 3.5 kg and a quasi-isometric task where a sinusoidal trace was followed with an extended arm without additional weight. Wang et al. (2021) included an isometric and a lifting task without additional mass in the protocol. The arms were flexed 100° during the isometric task and in the lifting task the shoulder flexion ranged from 0 to 100°.

All 12 shoulder exoskeleton field assessment protocols contained customised tasks (Claramunt et al., 2019; De Bock et al., 2021; de Vries et al., 2021; Ferreira et al., 2020; Gillette and Stephenson, 2018; Gillette and Stephenson, 2019; Hefferle et al., 2020; Iranzo et al., 2020; Moyon et al., 2018; Smets, 2019; Spada et al., 2018; Wang et al., 2021). These tasks were typical daily tasks of the industry of interest, i.e. automotive (Ferreira et al., 2020; Gillette and Stephenson, 2018; Gillette and Stephenson, 2019; Hefferle et al., 2020; Iranzo et al., 2020; Smets, 2019; Spada et al., 2018), logistics (De Bock et al., 2021), construction (de Vries et al., 2021), ship maintenance (Moyon et al., 2018) and farming (Wang et al., 2021).

### *3.5.3. Other exoskeletons*

In line with the variation in devices in this exoskeleton category, a large variety of tasks was observed in the assessments protocols.

*3.5.3.1. Validation assessment.* Three validation studies included a isometric seated posture at different heights in the assessment protocol (Han et al., 2019; Aida et al., 2009; Wijegunawardana et al., 2019). The knee flexion during these isometric tasks ranged from 20 to 60° and weights with masses of 10 or 20 kg were used. Two studies also executed the exercise without additional weight (Han et al., 2019; Wijegunawardana et al., 2019). In 6 studies lifting tasks were executed (Hao et al., 2020; Hondzinski et al., 2019; Otten et al., 2018; Jeong et al., 2020; Sasaki and Takaiwa, 2014; Yu et al., 2019). Elbow exoskeletons were assessed through 4 to 5 elbow flexion repetitions with 0–6 kg of additional mass in the hands (Hao et al., 2020; Otten et al., 2018). Leg exoskeletons were assessed through the execution of 2–10 squat lifting repetitions without additional weight (Yu et al., 2019; Jeong et al., 2020; Sasaki and Takaiwa, 2014), or with the maximal acceptable weight (Hondzinski et al., 2019). Two studies, assessing exoskeletons for loaded walking, included a loaded walking task where participants walked at 3 km/h with 10 and 20 kg (Kim et al., 2015; Lim et al., 2015). The duration of the tasks was not specified. Functional tasks, assessing kneeling, sit-to-stand, climbing stairs and walking, were included in 2 studies (Kim et al., 2020b; Hondzinski et al., 2019).

*3.5.3.2. Evaluation assessment.* Six out of the 7 evaluation studies assessed sitting exoskeletons and included a isometric sitting task (Bridger et al., 2018; Luger et al., 2019; Muramatsu et al., 2011; Pillai et al., 2020; Steinhilber et al., 2020; Xiloyannis et al., 2019; Zhu et al., 2018). The working height during these evaluations ranged from ground to hip level and knee flexion ranged from 25 to 90°. These tasks were performed without additional mass (Zhu et al., 2018; Bridger et al., 2018; Luger et al., 2019; Steinhilber et al., 2020), with a drilling tool (Pillai et al., 2020), or with 3 kg (Steinhilber et al., 2020). Muramatsu et al. (2011) assessed a full-body exoskeleton through a isometric posture with the upper body 30° tilted and the elbows 90° flexed while holding a weight with a mass of 20 kg. This exoskeleton was also evaluated through a lifting task where a weight of 20 kg was lifted 3 times from the ground until hip level (Muramatsu et al., 2011). An elbow exoskeleton was evaluated through an isometric task with the elbow 90° flexed while holding a mass of 3% of the body weight for 15 s (Xiloyannis et al., 2019). Additionally, a dynamic lifting task was performed with this exoskeleton. Participants flexed the elbow while following a GUI with a mass of 1 kg in the hand (Xiloyannis et al., 2019).

## *3.6. Overview of outcome parameters*

The effect of an exoskeleton on the wearer can be assessed through a variety of parameters. Torricelli and colleagues (Torricelli et al., 2020) suggested to divide exoskeleton assessments into assessment of functional performance and user experience.

### *3.6.1. Functional performance*

Within the functional performance pillar, electromyography (EMG) was most commonly reported (75%), other physiological parameters were used in 18% of the included papers (section 3.6.1.3). In 37% of all included studies, biomechanical outcomes were reported and 16% of the included papers reported exoskeleton parameters, i.e. data directly related to the exoskeleton, such as encoder, load cell, or torque sensor data.

*3.6.1.1. Electromyographic indicators.* The selection of muscles to monitor during an exoskeleton assessment depended on the exoskeleton category. An overview of the muscles monitored per exoskeleton category was provided in Fig. 5. Studies assessing back exoskeletons most frequently gathered EMG data from erector spinae longissimus muscle in the lumbar (72%) or thoracic region (42%), followed by monitoring activity in rectus abdominis (27%), erector spinae iliocostalis (18%) and external obliqui (18%). Shoulder exoskeleton evaluations most frequently tracked the EMG signal from deltoideus anterior (60%), biceps brachii (36%), trapezius descendens (30%), deltoideus medialis (28%) and triceps brachii (23%). In the other exoskeleton category, muscles in the lower and upper extremities, such as vastus lateralis (38%), rectus femoris (38%), gastrocnemius (29%) and biceps brachii (24%), were most frequently captured.

*3.6.1.2. Biomechanical indicators.* An overview of the reported biomechanical parameters per exoskeleton category was provided in Fig. 6. Similar to monitoring muscle activity, the papers focused on the region where the exoskeleton interfaced with the user. In back exoskeleton studies reporting biomechanical data, trunk flexion inclination was the most frequently reported biomechanical parameter (18%). Other parameters were hip angles (17%), knee angles (13%), lumbar angles (11%) and lumbar torque (11%). The shoulder joint angles (21%), elbow angles (13%) and shoulder torque (4%) were most commonly reported when assessing shoulder exoskeletons. Additionally, centre of pressure trajectories were used in 4% of the studies using biomechanical parameters assessing shoulder exoskeletons to grade the stability of the user while wearing the exoskeleton. In the other category, knee, hip and ankle angles were reported in 19%, 14% 10% of the papers, respectively. Stability was investigated by monitoring the centre of pressure displacement in 14% of the studies.

*3.6.1.3. Physiological indicators.* Out of the 25 studies that included physiological parameters, 60% reported heart rate. Respiratory measures were used in 40% of the studies reporting physiological data. Energy expenditure or metabolic cost were reported in 20%, 16% reported oxygen consumption and 4% reported breathing volume. Additionally, one study reported heart rate variability and another paper investigated blood pressure.

*3.6.1.4. Other.* Out of the 22 papers that reported exoskeleton measurements during the assessment, 50% reported the position of the exoskeleton's actuated joint. Most of these papers (41%) used the exoskeleton's torque-angle profile to reconstruct the provided support during the assessment. The exoskeleton's support was reconstructed directly through force measurement at the exoskeletons end-effector (5%), indirectly by measuring the force at the side of the actuator (32%), or by measuring deformation of the exoskeleton's spring (5%). Two studies determined the supportive characteristics of the exoskeleton empirically on a test bench (9%).

### *3.6.2. User experience*

User experience was assessed through subjective parameters, task performance parameters and cognitive parameters, occurring in 43%, 21% and 1% of the studies, respectively.

The user experience was captured by subjective measurements. Discomfort (48%) and rating of perceived exertion (47%) were most frequently included as subjective measure. Other topics of interest were effectiveness (20%), usability (18%), perception of range of motion

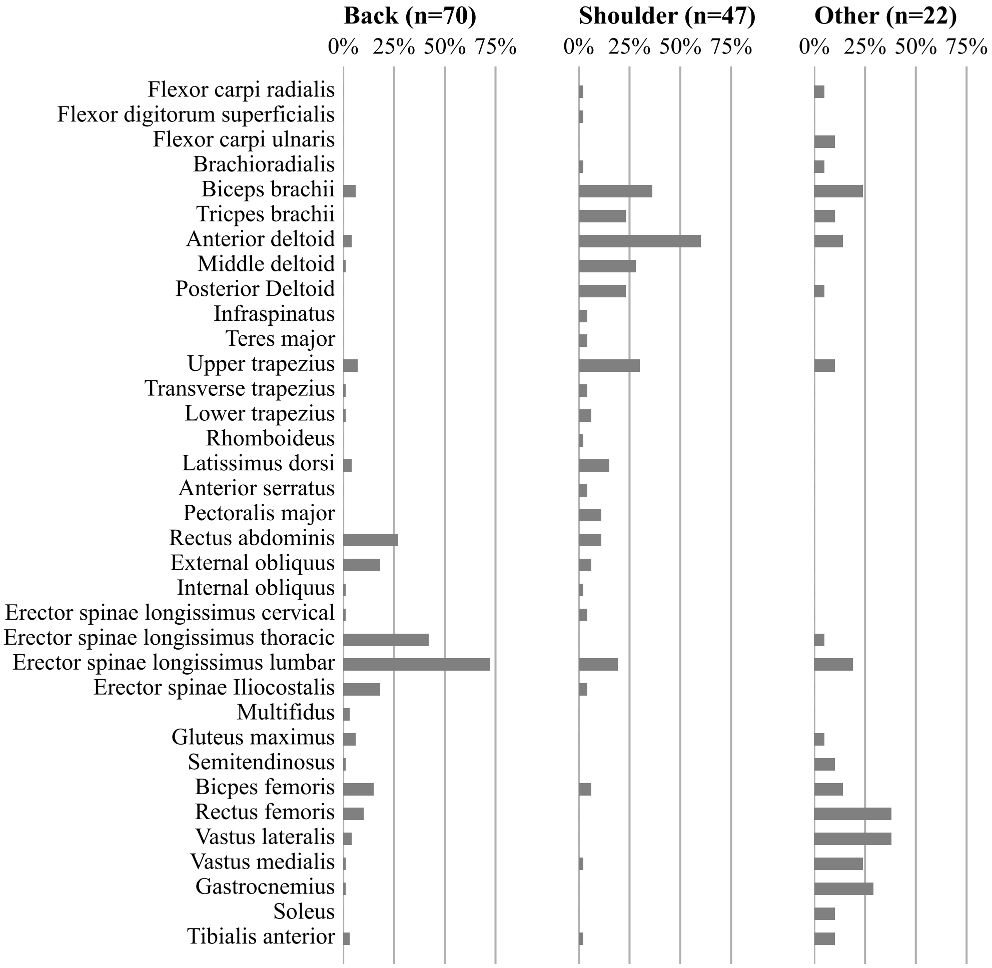

**Fig. 5.** The relative frequency, expressed as a percentage of all exoskeletons per category, at which EMG signals of muscles were measured during back, shoulder and other exoskeleton assessments is illustrated. Muscles were ordered from the hand towards the trunk and towards the feet.

(17%), obstruction (10%), pressure (10%) and workload (8%). Task performance was quantified by the completion time of a task in 48% of the studies reporting physical performance parameters. Endurance of a task was monitored in 34% of the studies and in 28% of the studies the total amount of work was quantified. Other studies measured the amount of errors (17%), precision (10%), strength (7%), smoothness of a movement (3%), and donning and doffing time (3%).

## 4. Discussion

In this evidence mapping systematic review, we propose a literature-based framework for benchmarking the effect of occupational exoskeletons on the user, after an overview of the literature concerning occupational exoskeleton assessment was provided. The retrieved exoskeleton assessments were heterogeneous, leading to a wide range of exoskeleton assessment strategies, which is a natural result of the wide range of occupational requirements, exoskeletal designs and goals, research questions and the multitude of occupational sectors the exoskeletons aim to target. This heterogeneity complicates exoskeleton benchmarking, and impedes systematic reviews to add a meta-analysis and compare the effects of exoskeletal devices (McFarland and Fischer, 2019; Kermavnar et al., 2021; Pesenti et al., 2021). As a result, keeping an overview and comparing devices remains challenging for both ergonomists and exoskeleton designers. The recommendations in the current review direct towards an occupational exoskeleton benchmarking framework.

### *4.1. Exoskeleton assessment, a dynamic process*

Although exoskeleton assessment is steered towards a linear sequence of discrete assessment categories through technology readiness levels (TRL) (European Commission, 2014), the evidence mapping process of this review pointed out that assessment of a device is a dynamic and continuously changing process (Figs. 2 and 4). Starting from this dynamic behaviour, this systematic review proposed three exoskeleton assessment categories, in which the protocol can be adjusted to provide information tailored to respond to the research question. A validation study is typically conducted to verify whether a concept provides the desired effect. While this category typically contained proof-of-concept studies of novel exoskeleton concepts, this type of studies can also be utilised to validate specific concepts inside more mature exoskeletons throughout the road to market introduction. These experiments require a highly controlled environment, and a limited sample size is acceptable. Therefore, these tests allow for fast prototyping adaptations in the agile development environment. Device evaluation aims to investigate the effect of an exoskeleton on the user in a relatively controlled, yet mildly applied setting, where statistical power is a critical element. Once devices reach a certain maturity and become more robust, field assessments become relevant. The dynamic process from concept validation to applied exoskeleton assessments in the field is a continuous process with a trade-off between experimental control and representativeness of the experimental design. Additionally, this process shows a non-linear behaviour, since new components, or adaptations in design may require validation before continuing with

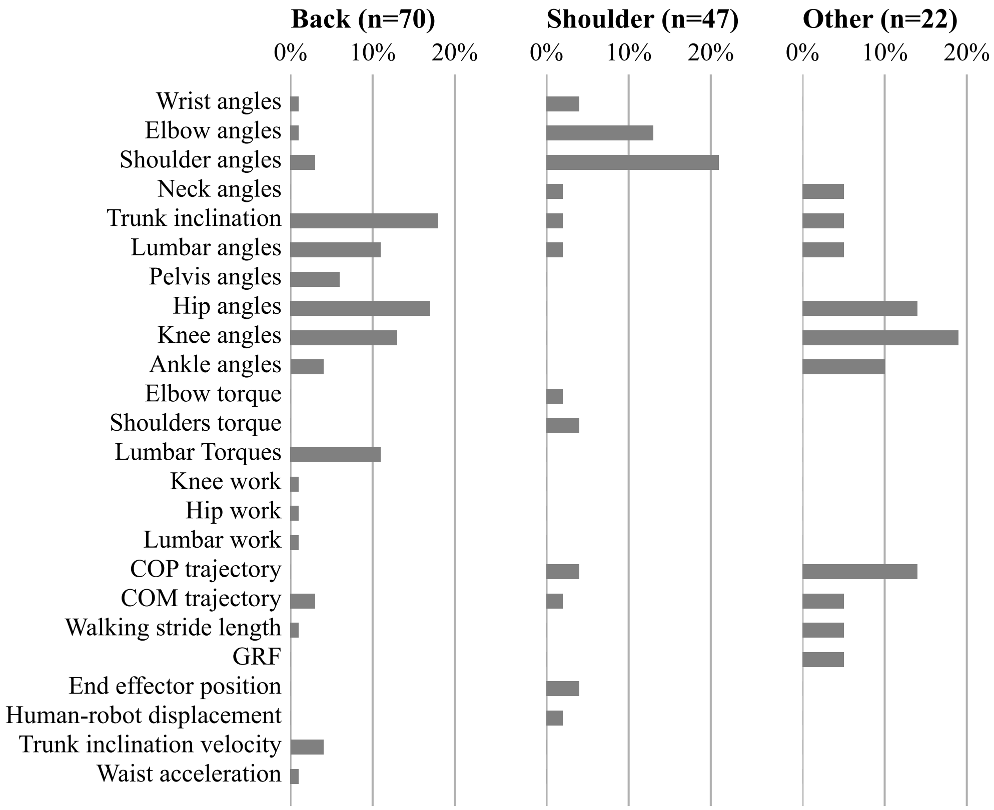

**Fig. 6.** The relative frequency, expressed as a percentage of all exoskeletons per category, at which biomechanical measures were collected during back, shoulder and other exoskeleton assessments is illustrated.

more applied assessments.

Depending on the type of exoskeleton assessment, different tasks and measurements were included in the protocol. In the tasks used during exoskeleton assessments, a transition from isometric towards customised tasks was observed as the exoskeleton and its assessment progress from validation to field studies. The majority of the tasks typically focus on the functional space of the exoskeleton, however, at a certain point in the development or implementation of a device, one should also investigate the effect of the device beyond its functionality. This is illustrated by the study of Baltrusch et al. (2018), who investigated the ability to climb a ladder with a passive back exoskeleton within the validated test battery for functional performance (Kozinc et al., 2020b). In

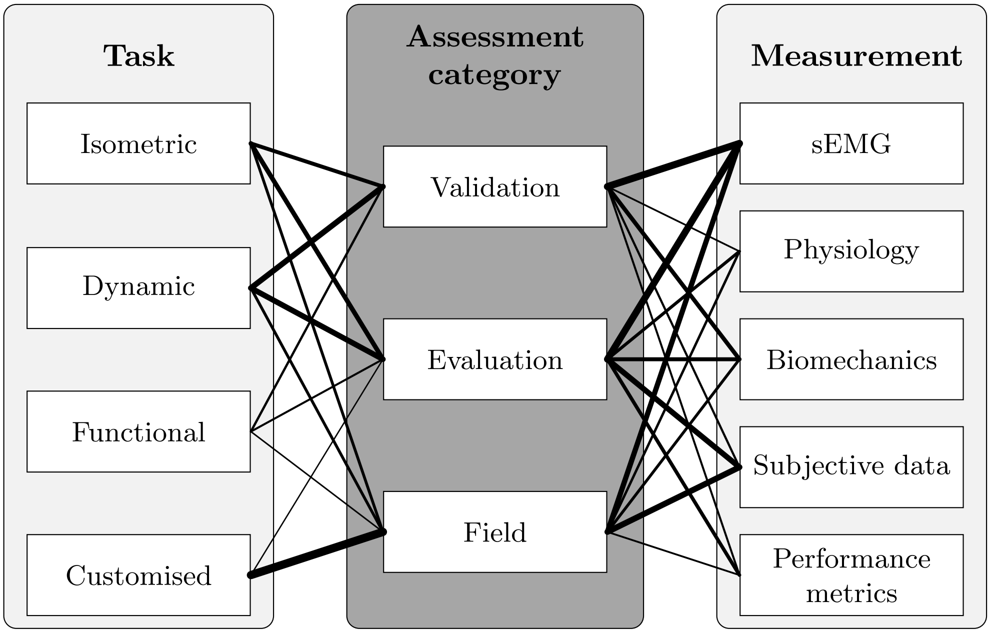

**Fig. 7.** Assessment types are connected with task and measurement categories. The thickness of the connection between the nodes corresponds with the relative frequency of occurrence of the task or measurement within each assessment type within the included papers in this evidence mapping review. The thicker the connection, the more frequently the task or measurement was observed per assessment type.

measurement variables, a subtle transition was observed from validation to field studies. Although EMG overall most frequently gathered, the use of subjective data increased from validation to field studies. This general framework, presented in Fig. 7, illustrates this observed dynamic process through connections from the assessment category to tasks and measurements that were observed in the included studies. Moreover, the thickness of each connection corresponds to the frequency of occurrence of the task or measurement within each assessment type.

### *4.2. The road towards a literature-based assessment framework*

To improve exoskeleton benchmarking, the following guidelines, based on the assessment methodologies of all 139 included papers, are formulated. When considering an exoskeleton assessment, one should decide the desired assessment category. In order to design a specific, yet repeatable and comparable assessment protocol, it is recommended to start from the research question in combination with the assessment category, after which the applicable tasks and outcomes of interest can be selected.

For validation experiments, researchers should aim for an assessment protocol tailored towards the research question, where parameters outside the scope of the research question are controlled. Therefore, validation studies typically focus on isometric or dynamic tasks and measure primarily EMG, complemented with biomechanical data describing the movement or posture. An extended user experience assessment is less common in this assessment category. Nevertheless, the value of such user-centred approach was recently emphasised in literature (Davis et al., 2020), and should receive more attention throughout validation studies of exoskeletal devices. The current framework contributes to a more aligned, yet fast and informative validation process where the controlled experimental setting plays a central role.

Evaluation experiments aim to assess the device in a more applied, yet controlled setting. These experiments can contain isolated and dynamic tasks, but also functional and customised tasks can be included in the protocol. Evaluation studies can comprise all measurement categories. Even though physiological data and task performance metrics are very relevant in this controlled, yet applied test environment, these types of measurement were less frequent in this type of assessment.

In field assessments, tasks are customised and most parameters are context dependent. Recommendations on test setting specifications are less relevant, however it must be emphasised that a detailed description of the working environment is crucial. Similar to customised tasks in evaluation experiments, it is recommended to quantify work characteristics that cannot be controlled as a measure of task performance during these experiments. Additionally, time pressure can be present and may vary over time in a work context. Controlling for, or quantifying this variable when executing tests in a field environment is recommended. This environment is challenging, because few variables can be controlled and practical limitations regarding infrastructure can be a burden. Subjective data comprising information regarding user experience was most commonly used.

#### *4.2.1. Tasks*

*4.2.1.1. Isometric tasks.* If only a limited number of tasks can be studied, the recommendation is a standing posture with 60° trunk flexion, the most commonly used flexion angle in validation experiments. This amount of trunk flexion elicits a gravitational flexion moment during isometric stooped postures, while avoiding a load shift from the active to passive structures of the back muscles (Koopman et al., 2019a). When the amount of tasks within the assessment of a shoulder exoskeleton is restricted, an isometric upright posture with 90° shoulder flexion and an extended elbow joint is advised. This was the most commonly used posture in the included literature, and provokes the maximal gravitational torque around the shoulder joint. In current studies external loads with masses between 0 and 25 kg have been used for back exoskeletons, and 0 and 17 kg for shoulder exoskeletons. These are the ranges with median values of 10 and 1.8 kg for back and shoulder exoskeletons, respectively. Although these median masses correspond to the masses of potential loads in occupational settings, it should be mentioned that these values are dependent on the capability of the exoskeleton and the likely application of the exoskeleton. The duration of isometric tasks in current literature ranged from 2.5 s to 5 min. Although the preferred duration is often context dependent, 3 10-s bouts can be executed to investigate the acute effect of exoskeleton support.

For evaluation studies, a more applied setting is preferred. Back exoskeleton evaluations could perform a quasi-isometric work simulation, such as a grooved pegboard test with the trunk 60° flexed and without additional weight [e.g. 117]. For shoulder exoskeleton evaluations, quasi-isometric wiring or drilling tasks were used most often in literature [e.g. 106]. The recommended overhead working height is defined as $a + 0.4(b - a)$ by Sood et al. (2007), with *(a)* hand height with the shoulder and elbow flexed at 90° and *(b)* hand height with the upper arm in full extension. Work at this height imposed substantial arm elevation, while avoiding the end range-of-motion of the upper extremity. Similar to the validation studies, tools of 1.8 kg are recommended for drilling simulations, wiring simulations can be performed without additional masses. The average duration of quasi-isometric tasks was 90 s, but some studies linked task duration to completion of a task, or endurance capacity. The latter could provide additional information.

*4.2.1.2. Dynamic tasks.* To assess the acute effect of an exoskeleton A pace of 3 lifting cycles per minute during dynamic tasks allows for a resting phase between repetitions and a detailed analysis of EMG and biomechanics in the time domain. Ten repetitions per subject with the recommended masses generate an impression of the intra-subject distribution per parameter, without provoking fatigue. Lifting tasks should start and end in a neutral standing position, and cover the most common range of motion in an occupational setting. A lifting cycle for back exoskeletons includes (*i*) reaching for the weight with handles 10 cm above ankle height, (*ii*) lifting the weight, (*iii*) lowering the weight and (*iv*) returning to the starting position, e.g. (Koopman et al., 2020). The most common lifting techniques were symmetric and asymmetric free lifting, stoop, squat and semi squat lifting. Most lifting tasks with a shoulder exoskeleton ranged from a neutral standing position up to 90° shoulder flexion and back to the neutral position. However, covering a larger range of motion, up to 150° (de Vries et al., 2019) could provide additional information. These recommendations apply for validation and evaluations studies, but to quantify metabolic cost or cardiovascular parameters during a dynamic task, it is recommended to maintain a higher and constant pace (JONES and POOLE, 2005). These parameters are characterised with a delayed response to work related impulses, e.g. oxygen deficit after an increase in exercise intensity (Poole and Jones, 2012). Therefore, it is recommended to lift for at least 5 min and maintain a pace of 8 lifts per minute with 10 (Baltrusch et al., 2020a) or 1.8 kg (Park and Cho, 2017) for back and shoulder exoskeletons, respectively. These lifting paces and masses can also be used in studies investigating development of peripheral fatigue, but more repetitions may be required. Based on the protocols focusing on peripheral fatigue, it is recommended to include at least 100 lifting cycles (Godwin et al., 2009; Lotz et al., 2009; Lamers et al., 2020; Yin et al., 2019). Furthermore, standardised lifting techniques such as stoop or squat lifts are only a minor representation of real occupational work, because weights are not moved from one location to another. Symmetric and asymmetric lifting tasks where weights are moved from one place to another, e.g. the lifting tasks described in Alemi et al. (2020), are valuable for future device evaluations.

*4.2.1.3. Functional tasks.* The majority of functional tasks was observed in evaluation assessments. These tasks are interesting to explore the effect of the exoskeleton beyond the specific task it was designed for. Relevant examples of functional tasks are walking with an exoskeleton, and donning and doffing time. Although most occupational exoskeletons are not supporting these tasks, both tasks are common in all occupational settings. For back exoskeletons, the functional task battery of Baltrusch and colleagues (Baltrusch et al., 2018), which was recently validated (Kozinc et al., 2020b), is recommended. For shoulder and other exoskeletons such validated test battery was not yet developed.

*4.2.1.4. Customised tasks.* In field assessments, but also in evaluation studies, protocols can be adapted to a specific situation in the field. These customised tasks could include actual working heights, paces, weights and set-up dimensions, e.g. (Kinne et al., 2020). When working pace, volume, height or endurance cannot be controlled, these parameters can serve as performance metrics instead of predetermined experimental characteristics.

### 4.3. Additional efforts to improve assessment quality

This review's risk of bias assessment pointed out that a randomised order of experimental conditions was not always applied and none of the studies blinded participants or investigators. To further improve the quality of future studies, effort into randomisation of conditions and participant blinding is needed in this field. Evidently, blinding is not obvious, given the physical presence of exoskeletons on the user, or the obvious difference between a novel prototype and a commercially available device. However, researchers should be aware that the absence of blinding could induce placebo or nocebo effects. Similar to the placebo and nocebo effect in medicine and sports performance (Benedetti, 2014; Hurst et al., 2020), the exoskeleton's expected effect can affect the device assessment's outcomes and increase variability in the response to exoskeletons (Beedie et al., 2020). While the placebo and nocebo effect of exoskeletons could be an interesting field of research, most assessment studies would benefit from avoiding expectancy differences between test conditions. This can be partially counteracted by hiding the exact aims and hypothesis of the study from participants with a deceiving research question, creating so-called naive participants (Van Cutsem et al., 2017). The physical presence of an exoskeleton can still create differences in expectations, therefore we suggest hiding the exoskeleton characteristics and quantify how participants expect to perform on the task. Apart from expectation management, selection of the test sample could be improved, since in this review's included studies only 19% of all participants were occupational workers. Participants recruited from a convenience sample were younger and weighted less than the occupational workers. Additionally, for each female participant, 5 male participants were tested throughout all included papers. This ratio is in sharp contrast with the average occupational population, e.g. female workers account for 47% of all industrial workers in the U.S. (U.S. Bureau of labor Statistics, 2021). These discrepancies could significantly affect the exoskeleton's effectiveness and user experience, since body dimensions and composition of female individuals differ from men (Kirchengast, 2010). Arguably, a convenience sample can be used for a first validation of a device, but sample of actual workers will provide more realistic outcomes, especially when focusing on the fit and comfort and over-representation of male participants in studies may lead to exoskeleton designs that are sub-optimally built for female workers. Although reporting outcomes is beyond the scope of this review, an aligned data reporting strategy would contribute to the repeatability of the assessment framework and facilitate comparisons among studies. Only 16% of the papers in this review reported exoskeleton related measurements, such as the exoskeleton's support, yet it was shown that both positive and negative effects of passive exoskeletons change with the level of support (Van Engelhoven et al., 2019; Theurel et al., 2018). In active exoskeletons, transparency in control strategies is required to interpret the measured outcomes and control strategies should be verified in a representative field setting, to avoid undesired behaviour of the devices in unstructured scenarios. During the screening process of the papers in this review, it was remarkable that processing EMG signals differed from study to study. Furthermore, different features were derived from EMG data, e.g. peak amplitude, average amplitude and time-integrated amplitude. Some of these features were normalised, e.g. to maximal voluntary contraction, while others reported activity in microvolts. Inconsistency in processing and reporting outcomes adds to heterogeneity of the exoskeleton assessment palette and future work could aim to increase repeatability in this aspect of exoskeleton assessment.

### 4.4. Limitations and future research

The proposed framework is a next step towards a general exoskeleton benchmarking framework. Recommendations for a range of benchmarking scenarios were provided, but the current framework cannot cover the entire field of exoskeleton assessment. Therefore, specific research questions may require deviations from the framework. The scope of this framework may be expanded over time, depending on the assessment needs. The majority of studies focused on back and shoulder exoskeletons, which lead to specific guidelines for these exoskeleton models. For other exoskeletons, such as elbow exoskeletons or devices that support a seated position, a wide pool of included papers was missing, which limited the options to define literature-based recommendations. Nevertheless, the general framework presented in this review applies for these exoskeletons too and could contribute to a generalised assessment strategy. Future complementary work could add specific assessment recommendations for other exoskeleton models. During the screening process of this review, the large variety of EMG processing and reporting techniques became apparent. Although this topic did not fit the current review, differences in EMG processing and reporting complicate comparison among studies. Future work could provide a more uniform method for approaching EMG data in exoskeleton assessment experiments. In addition, this work focused on human-centred device assessment, thus technical exoskeleton benchmarking was outside of the scope of this review. As more and more active exoskeletons are being developed, standardised assessments of actuator characteristics or control strategies may become warranted.

## 5. Conclusion

This evidence mapping systematic review included 139 studies containing a human-centred occupational exoskeleton assessment. After providing an overview of the wide variety of assessment methodologies, the conclusion is that the assessment of an occupational exoskeleton is a dynamic, and not necessarily linear process, with a continuous trade-off between experimental control and a representative experimental design. Subsequently, a literature-based assessment framework paving the path towards a unified benchmarking strategy for occupational exoskeletons was presented. Such strategy would substantially increase comparability of studies and facilitate meta-analyses in the future. In order to further improve the quality and comparability of assessment strategies, randomisation and blinding of experimental conditions deserve more attention and researchers should aim at recruiting actual workers more regularly. As the effect of the exoskeleton and its assistive characteristics are inherently connected, reporting empirical data of the exoskeleton's support would increase the value of future research. This review mapped the assessment strategies for occupational exoskeletons and highlighted inconsistencies in literature. Subsequently, a literature-based assessment framework to benchmark the effect of occupational exoskeletons on the user was presented.

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## Declaration of competing interest

S. Crea has interests in IUVO S.r.l., a spin-off company of Scuola Superiore Sant'Anna, which develops wearable robots. The other authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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## Appendix A

**Table A.1**
Summary of the risk of bias. B1 = Bias arising from randomisation process, B2 = Bias due to deviations from intended interventions, B3 = Bias due to missing outcome data, B4 = Bias in measurement of the outcome, B5 = Bias in selection of the reported result. (+): Low risk of bias, (?): Unclear risk of bias, (−): High risk of bias.

| Study | B1 | B2 | B3 | B4 | B5 |
|---|---|---|---|---|---|
| Grazi et al. (2020) | - | + | + | ? | + |
| Koopman et al. (2020) | - | + | + | ? | + |
| Baltrusch et al. (2020a) | ? | + | + | ? | + |
| Maurice et al. (2020) | - | + | + | - | + |
| Aida et al. (2009) | - | + | + | ? | - |
| Blanco et al. (2019) | ? | + | + | ? | + |
| Chen et al. (2018) | - | + | + | ? | + |
| De Busk et al. (2017) | ? | + | + | ? | + |
| de Vries et al. (2019) | - | + | + | ? | + |
| Ebrahimi et al. (2017) | - | + | + | ? | ? |
| Han et al. (2019) | - | + | + | ? | + |
| Han et al. (2020) | - | + | + | ? | ? |
| Hao et al. (2020) | - | + | + | ? | + |
| Hondzinski et al. (2019) | ? | + | + | ? | ? |
| Hull et al. (2020) | + | + | + | ? | + |
| Huysamen et al. (2018a) | ? | + | + | ? | + |
| Inose et al. (2017) | ? | + | + | ? | ? |
| Inoue and Noritsugu (2018) | ? | + | + | ? | ? |
| Jeong et al. (2020) | ? | + | + | ? | ? |
| Johnson et al. (2018) | - | + | + | ? | ? |
| Kazerooni et al. (2019) | - | + | + | ? | ? |
| Kim et al. (2015) | - | + | + | ? | ? |
| Kim et al. (2018a) | ? | + | + | ? | ? |
| Kim et al. (2020a) | ? | + | + | ? | + |
| Kobayashi and Nozaki (2008) | ? | + | + | ? | ? |
| Koopman et al. (2019a) | ? | + | + | ? | + |
| Kosaki and Li (2020) | ? | + | + | ? | ? |
| Kudernatsch and Peterson (2018) | ? | + | + | ? | + |
| Kurita et al. (2017) | - | + | + | ? | + |
| Lamers et al. (2020) | - | + | + | ? | + |
| Lanotte et al. (2018) | - | + | + | ? | + |
| Lazzaroni et al. (2019) | - | + | + | ? | + |
| Lee et al. (2012b) | - | + | + | ? | + |
| Li et al. (2013) | - | + | + | ? | + |
| Lim et al. (2015) | - | + | + | ? | + |
| Lotti et al. (2020) | - | + | + | ? | ? |
| Luo and Yu (2013) | - | + | + | ? | - |
| Muramatsu et al. (2013) | - | + | + | ? | + |
| Näf et al. (2018) | ? | + | + | ? | + |
| Naruse et al. (2005) | ? | + | + | ? | + |
| Natividad et al. (2019) | ? | + | + | ? | + |
| Otten et al. (2018) | - | + | + | - | + |
| Park and Cho (2017) | - | + | + | ? | - |
| Sasaki and Takaiwa (2014) | - | + | + | ? | ? |
| Shin et al. (2019) | - | + | + | - | - |
| Sylla et al. (2014a) | ? | + | + | ? | + |
| Sylla et al. (2014a) | - | + | + | ? | - |
| Tiseni et al. (2019) | - | + | + | ? | + |
| Ulrey and Fathallah (2013) | ? | + | + | ? | + |
| Wehner et al. (2009) | - | + | + | ? | - |
| Wijegunawardana et al. (2019) | - | + | + | ? | + |
| Yong et al. (2017) | - | + | + | - | - |
| Yu et al. (2019) | - | + | + | ? | + |
| Zhang et al. (2016) | - | + | + | ? | + |
| Abdoli-E et al. (2006) | ? | + | + | ? | - |

(*continued on next page*)

**Table A.1** (*continued*)

| Study | B1 | B2 | B3 | B4 | B5 |
|---|---|---|---|---|---|
| Abdoli-Eramaki et al. (2007) | ? | + | + | ? | ? |
| Abdoli-E and Stevenson (2008) | ? | + | + | ? | ? |
| Alabdulkarim et al. (2019) | + | + | + | ? | - |
| Alabdulkarim and Nussbaum (2019) | + | + | + | ? | - |
| Alemi et al. (2019) | ? | + | + | ? | + |
| Alemi et al. (2020) | | | | | |
| Baltrusch et al. (2018) | ? | + | + | ? | ? |
| Baltrusch et al. (2019) | ? | + | + | ? | ? |
| Baltrusch et al. (2020b) | ? | + | + | ? | + |
| Bosch et al. (2016) | ? | + | + | ? | - |
| Bridger et al. (2018) | ? | + | + | ? | + |
| Daratany et al. (2020) | ? | + | + | ? | + |
| Frost et al. (2009) | ? | + | + | ? | ? |
| Gilotta et al. (2018) | ? | + | + | ? | + |
| Godwin et al. (2009) | - | + | + | ? | ? |
| Gorsic et al. (2020) | ? | + | + | ? | ? |
| Huysamen et al. (2018b) | ? | + | + | ? | + |
| Hyun et al. (2019) | ? | + | + | ? | + |
| Hyun et al. (2020) | ? | + | + | ? | + |
| Ji et al. (2020) | ? | + | + | ? | + |
| Kelson et al. (2019) | ? | + | + | ? | ? |
| Kim et al. (2018b) | ? | + | + | ? | + |
| Kim and Nussbaum (2019) | ? | + | + | ? | + |
| Kim et al. (2020b) | ? | + | + | ? | + |
| Kim et al. (2018c) | + | + | + | ? | ? |
| Kinne et al. (2020) | ? | + | + | ? | + |
| Ko et al. (2018) | | | | | |
| Koopman et al. (2019b) | - | + | + | ? | ? |
| Kozinc et al. (2020a) | ? | + | + | ? | ? |
| Lamers et al. (2018) | ? | + | + | ? | + |
| Lotz et al. (2009) | ? | + | + | ? | + |
| Luger et al. (2019) | - | + | + | ? | + |
| Madinei et al. (2020a) | ? | + | + | ? | + |
| Madinei et al. (2020b) | + | + | + | ? | + |
| Miura et al. (2018a) | + | + | + | ? | + |
| Muramatsu et al. (2011) | + | + | + | - | + |
| Pacifico et al. (2020) | - | + | + | - | - |
| Picchiotti et al. (2019) | ? | + | + | ? | + |
| Pillai et al. (2020) | ? | + | + | ? | + |
| Pinho et al. (2020) | ? | + | + | ? | + |
| Poliero et al. (2020) | ? | + | + | ? | + |
| Qu et al. (2021) | ? | + | + | ? | + |
| Sadler et al. (2011) | ? | + | + | ? | + |
| Schmalz et al. (2019) | ? | + | + | - | + |
| So et al. (2020) | ? | + | + | ? | + |
| Spada et al. (2017) | ? | + | + | ? | + |
| Spada et al. (2017) | + | + | + | ? | + |
| Steinhilber et al. (2020) | | | | | |
| Tan et al. (2019) | - | + | + | - | - |
| Theurel et al. (2018) | - | + | + | - | - |
| Toxiri et al. (2018) | + | + | ? | ? | ? |
| Van Engelhoven et al. (2019) | ? | + | + | ? | - |
| von Glinski et al. (2019) | ? | + | + | - | + |
| Wei et al. (2020a) | ? | + | + | ? | + |
| Wei et al. (2020b) | ? | + | + | - | + |
| Whitfield et al. (2014) | ? | + | + | - | + |
| Xiloyannis et al. (2019) | ? | + | + | - | - |
| Yin et al. (2019) | ? | + | + | ? | - |
| Yin et al. (2020) | ? | + | + | ? | - |
| Yong et al. (2019) | ? | + | + | ? | - |
| Lee and Chee (2013) | - | + | + | ? | - |
| Zhu et al. (2018) | ? | + | + | - | + |
| Amandels et al. (2019) | - | + | + | ? | + |
| Baltrusch et al. (2021) | - | + | + | - | - |
| Claramunt et al. (2019) | - | + | + | ? | + |
| De Bock et al. (2021) | ? | + | + | ? | - |
| de Vries et al. (2021) | ? | + | + | ? | - |
| Dewi and Komatsuzaki (2018) | ? | + | + | ? | + |
| Ferreira et al. (2020) | | | | | |
| Gillette and Stephenson (2018) | ? | + | + | ? | + |
| Gillette and Stephenson (2019) | ? | + | + | ? | ? |
| Graham et al. (2009) | ? | + | + | ? | + |
| Hefferle et al. (2020) | - | + | + | ? | + |
| Hensel and Keil (2019) | ? | + | + | ? | + |
| Iranzo et al. (2020) | ? | + | + | ? | + |
| Miura et al. (2018b) | ? | + | + | ? | ? |

(*continued on next page*)

**Table A.1** (*continued*)

| Study | B1 | B2 | B3 | B4 | B5 |
|---|---|---|---|---|---|
| Motmans et al. (2019) | ? | + | + | ? | + |
| Moyon et al. (2018) | ? | + | + | ? | + |
| Omoniyi et al. (2020) | - | + | + | ? | ? |
| Settembre et al. (2020) | - | + | + | - | - |
| Smets (2019) | - | + | + | - | - |
| Spada et al. (2018) | ? | + | + | ? | + |
| Thamsuwan et al. (2020) | ? | + | + | - | - |
| Wang et al. (2021) | - | + | + | - | + |

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