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Occupational Exoskeletons: A Roadmap Towards Large-Scale Adoption

Methodology and challenges of bringing exoskeletons to workplaces

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# Supplementary materials

Table 3. List of in-lab studies on upper-limb exoskeletons.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Study** | **Exoskeletons** | **Exoskeletons’ exploitation level** | **Subjects’ number and gender** | **Subjects’ level of experience** | **Biomechanical risk-related indexes** |
| *Alabdulkarim et al., 2019* | * Fortis, * ShoulderX, * Fawcett Exovest with zero-gravity arm | Market | 16 (8 male, 8 female) | Non-expert | n/a |
| *Blanco et al., 2019* | MovilFrio | Prototype | 10 (8 male, 2 female) | Non-expert | n/a |
| *Blanco et al., 2020* | ExIF project | Prototype | 12 (11 male, 1 female) | Non-expert | n/a |
| *de Vries et al., 2019* | Skelex | Market | 12 male | Non-expert | Total moment at the shoulder joint |
| *de Vries et al., 2021* | Skelex | Market | 11 male | Expert | n/a |
| *Grazi et al., 2020* | H-PULSE | Prototype | 10 male | Non-expert | n/a |
| *Huysamen et al., 2018a* | Robo-Mate | Prototype | 8 (4 male, 4 female) | Non-expert | n/a |
| *Hyun et al., 2019* | H-VEX | Pre-Market | 10 male | Non-expert | n/a |
| *Kelson et al., 2019* | * EksoVest, * Levitate Airframe | Market | 11 (7 male, 4 female) | Non-expert | n/a |
| *Kim et al., 2019* | EksoVest | Market | 12 (6 male, 6 female) | Non-expert | n/a |
| *Kim et al., 2018a* | Proto-EksoVest | Pre-Market | 12 (6 male, 6 female) | Non-expert | n/a |
| *Kim et al., 2018b* | Proto-EksoVest | Pre-Market | 27 (14 male, 13 female) | Non-expert | n/a |
| *Maurice et al., 2019* | Paexo | Market | 12 male | Non-expert | n/a |
| *Moyon et al., 2019* | Skelex | Market | 36 (18 male, 18 female) | Non-expert | n/a |
| *Otten et al., 2018* | Lucy 2.0 | Prototype | 3 (2 male, 1 female) | Non-expert | n/a |
| *Pacifico et al., 2020* | Proto-MATE | Pre-Market | 15 male | Non-expert | n/a |
| *Perez Luque et al., 2020* | * EksoVest, * Paexo, * MATE | Market | 17 (11 male, 6 female) | 8 expert, 9 non-expert | n/a |
| *Pinho et al., 2020* | * ShoulderX, * MATE, * Paexo | Market | 2 male | Expert | n/a |
| *Rashedi et al., 2014* | WADE | Prototype | 12 male | Non-expert | n/a |
| *Schmalz et al., 2019a* | Paexo | Market | 12 (6 male, 6 female) | Non-expert | n/a |
| *Schmalz et al., 2019b* | Paexo | Market | 12 (6 male, 6 female) | Non-expert | n/a |
| *Spada et al., 2018a* | Levitate Airframe | Market | 42 male | Expert | n/a |
| *Spada et al., 2017* | Levitate Airframe | Market | 29 male | Expert | n/a |
| *Spada et al., 2018b* | Proto-MATE | Pre-Market | 18 male | Expert | n/a |
| *Sylla et al., 2014* | ABLE | Prototype | 8 male | Non-expert | Sum of joint torques |
| *Theurel et al., 2018* | EXHAUSS Stronger | Prototype | 8 (4 male, 4 female) | Non-expert | n/a |
| *Van Engelhoven et al., 2019* | ShoulderX | Market | 14 male | Expert | n/a. |
| *Wang et al., 2021* | PULE | Prototype | 18 male | Expert | n/a |
| *Yin et al., 2020* | PULE | Market | 15 male | Non-expert | n/a |

Table 4. List of in-field studies on upper-limb exoskeletons.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Study** | **Exoskeletons** | **Exoskeletons’ exploitation level** | **Subjects’ number and gender** | **Subjects’ level of experience** | **Biomechanical risk-related indexes** |
| *De Bock et al., 2020* | * ShoulderX, * Skelex | Market | 4 male | Expert | n/a |
| *Gillette & Stephenson, 2019* | Levitate Airframe | Market | 6 (4 male, 2 female) | Expert | n/a |
| *Gillette & Stephenson, 2018* | Levitate Airframe | Market | 11 male | Expert | n/a |
| *Hefferle, et al., 2021* | Crimson Dynamics,  Skelex V1 | Market | 8 male | Expert | n/a |
| *Iranzo et al., 2020* | Levitate Airframe | Market | 12 (11 male, 1 female) | Expert | n/a |
| *Moyon et al., 2018* | Skelex | Market | 9 (5 male, 4 female) | Expert | n/a |
| *Smets et al., 2019* | EksoVest | Market | 10 (9 male, 1 female) | Expert | n/a |
| *Wang et al., 2021* | PULE | Prototype | 8 male | Expert | n/a |

Table 5. List of in-lab studies on back-support exoskeletons.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Study** | **Exoskeletons** | **Exoskeletons’ exploitation level** | **Subjects’ number and gender** | **Subjects’ level of experience** | **Biomechanical risk-related indexes** |
| *Abdoli-E et al., 2006a* | * PLAD | Prototype | 9 male | Non-expert | n/a |
| *Abdoli-E et al., 2008* | * PLAD | Prototype | 9 male | Non-expert | Integrated moments about L4/L5 joint |
| *Abdoli-E et al., 2006b* | * PLAD | Prototype | 9 male | Non-expert | Percentage of compression and shear reduction on L4/L5 joint  Peak reaction force and pressure on L4/L5 joint |
| *Alemi et al., 2019* | * VT-Lowe | Prototype | 12 male | Non-expert | n/a |
| *Alemi et al., 2020* | * BackX, * Laevo | Market | 18 (9 male, 9 female) | Non-expert | n/a |
| *Baltrusch et al., 2020a* | * SPEXOR | Prototype | 17 male | Expert | Knee, hip, L5/S1 joints mechanical work |
| *Baltrusch et al., 2020b* | * SPEXOR | Prototype | 10 male | Expert | n/a |
| *Baltrusch et al., 2020c* | * SPEXOR | Prototype | 24 male | Expert | n/a |
| *Baltrusch et al., 2018a* | * Laevo | Market | 18 male | Non-expert | n/a |
| *Baltrusch et al., 2018b* | * Laevo | Market | 18 male | Non-expert | n/a |
| *Baltrusch et al., 2019* | * Laevo | Market | 18 male | Non-expert | n/a |
| *Bosch et al., 2016* | * Laevo | Market | 18 male (9 male, 9 female) | Non-expert | n/a |
| *Chen et al., 2018* | * APO | Prototype | 7 male | Non-expert | n/a |
| *Dewi et al., 2018* | * PAS | Prototype | 13 (7 male, 6 female) | Expert | n/a |
| *Frost et al., 2009* | * PLAD | Prototype | 13 male | Non-expert | Integrated L4/L5 joint moment |
| *Goršič et al., 2019* | * Modular reconfigurable trunk exoskeleton | Prototype | 12 (11 male, 1 female) | Non-expert | n/a |
| *Han et al., 2019* | * Exoskeleton with passive storage mechanism | Prototype | 3 | Non-expert | n/a |
| *Heo et al., 2020* | * Pneumatic back-support exoskeleton | Prototype | 10 male | Non-expert | n/a |
| *Hussain et al., 2020* | * Exoskeleton for lifting | Prototype | 10 (7 male, 3 female) | Non-expert | n/a |
| *Huysamen et al., 2018b* | * Robo-Mate | Prototype | 12 male | Non-expert | Contact pressure |
| *Hyun et al., 2020* | * H-WEX V2 | Prototype | 10 male | Non-expert | n/a |
| *Inose et al., 2017* | * AB-Wear | Prototype | 1 male | Non-expert | n/a |
| *Kazerooni et al., 2019* | * BackX | Market | 8 (4 male, 4 female) | Non-expert | n/a |
| *Kim et al., 2020* | * BackX, * Laevo V2.5 | Market | 18 (9 male, 9 female) | Non-expert | n/a |
| *Ko et al., 2018* | * H-WEX | Prototype | 9 male | Non-expert | n/a |
| *Kobayashi et al., 2008* | * Muscle Suit | Prototype | 3 male | Non-expert | n/a |
| *Koopman et al. 2020a* | * SPEXOR | Prototype | 10 male | Expert | Compression force and moment at L5/S1 joint |
| *Koopman et al., 2019a* | * Laevo | Market | 11 male | Non-expert | Net L5/S1 moment |
| *Koopman et al., 2020b* | * Laevo V2.4 | Market | 11 male | Non-expert | Peak compression forces on L5/S1 disc  Peak L5/S1 joint moment |
| *Koopman et al., 2019b* | * Mk2B (Robo-Mate 2nd version) | Prototype | 10 male | Non-expert | Peak compression forces on L5/S1 disc  Peak L5/S1 joint moment |
| *Kozinc et al., 2020a* | * SPEXOR | Prototype | 20 (10 male, 10 female) | Non-expert | n/a |
| *Kozinc et al., 2020b* | * SPEXOR | Prototype | 14 (7 male, 7 female) | Non-expert | n/a |
| *Lamers et al., 2018* | * Garment with elastic bands | Prototype | 8 (7 male, 1 female) | Non-expert | Intervertebral compression disc (estimate) |
| *Lanotte et al., 2018* | * APO | Prototype | 5 male | Non-expert | n/a |
| *Lazzaroni et al., 2019* | * Robo-Mate | Prototype | 7 male | Non-expert | n/a |
| *Lotz et al., 2009* | * PLAD | Prototype | 10 male | Non-expert | n/a |
| *Luo et al., 2013* | * WSAD | Prototype | 1 male | Non-expert | n/a |
| *Madinei et al., 2020a* | * BackX, * Laevo | Market | 18 (9 male, 9 female) | Non-expert | n/a |
| *Madinei et al., 2020b* | * BackX, * Laevo | Market | 18 (9 male, 9 female) | Non-expert | n/a |
| *Miura et al., 2020a* | * HAL for Care Support | Market | 19 (16 male, 3 female) | Non-expert | n/a |
| *Miura et al., 2020b* | * HAL for Care Support | Market | 18 (11 male, 7 female) | Non-expert | n/a |
| *Naf et al, 2018* | * SPEXOR | Prototype | 3 male | Non-expert | n/a |
| *Omoniyi et al., 2020* | * Laevo | Market | 15 (14 male, 1 female) | Expert | n/a |
| *Picchiotti et al., 2019* | * StrongArm Technologies FLx, * StrongArm Technologies V22 | Market | 10 male | Non-expert | Peak sagittal moment on L5/S1 joint  Spinal loading for compression and shear at L3/L4 and L5/S1 joints |
| *Poliero et al., 2020* | * XoTrunk | Prototype | 9 male | Non-expert | n/a |
| *Qu et al., 2021* | * IPAE | Pre-market | 8 male | Expert | n/a |
| *Shin et al., 2019* | * Pneumatic muscle-based back assistance exoskeleton | Prototype | 1 male | Non-expert | n/a |
| *So et al., 2020* | * BackX | Market | 30 (20 male, 10 female) | Expert | n/a |
| *Tan et al., 2019* | * HAL for Care Support | Market | 20 (13 male, 7 female) | Non-expert | n/a |
| *Thamsuwan et al., 2020* | * Laevo | Market | 14 (13 male, 1 female) | Expert | n/a |
| *Toxiri et al., 2018* | * Robo-Mate | Prototype | 11 male | Non-expert | n/a |
| *von Glinski et al., 2019* | * HAL for Care Support | Market | 14 male | Non-expert | n/a |
| *Wei et al., 2020* | * MeBot-EXO | Prototype | 7 male | Non-expert | n/a |
| *Weston et al., 2018* | * Steadicam Fawcett Exoskeletal vest | Market | 12 male | Non-expert | Compression and shear forces on L4/L5 and L5/S1 joints |
| *Whitfield et al., 2013* | * PLAD | Prototype | 15 male | Non-expert | n/a |
| *Yong et al., 2019* | * SIAT waist exoskeleton | Prototype | 10 | Non-expert | n/a |
| *Zhang et al., 2018* | * Lower back robotic exoskeleton | Prototype | 1 male | Non-expert | n/a |

Table 6. List of in-field studies on back-support exoskeletons.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Study** | **Exoskeletons** | **Exoskeletons’ exploitation level** | **Subjects’ number and gender** | **Subjects’ level of experience** | **Biomechanical risk-related indexes** |
| *Amandels et al., 2018* | * Laevo | Market | 9 male | Expert | n/a |
| *Graham et al., 2009* | PLAD | Prototype | 10 (8 male, 2 female) | Expert | Compression normalized EMG for spinal compression |
| *Hensel & Keil, 2019* | * Laevo | Market | 30 male | Expert | n/a |
| *Motmans et al., 2019* | * Laevo V2.5 | Market | 10 male | Expert | n/a |
| *Settembre et al., 2020* | Laevo | Market | 2 male | Expert | n/a |