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Review Article

Review and Evaluation of Hand–Arm Coordinate Systems for Measuring Vibration Exposure, Biodynamic Responses, and Hand Forces

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ABSTRACT

The hand coordinate systems for measuring vibration exposures and biodynamic responses have been standardized, but they are not actually used in many studies. This contradicts the purpose of the standardization. The objectives of this study were to identify the major sources of this problem, and to help define or identify better coordinate systems for the standardization. This study systematically reviewed the principles and definition methods, and evaluated typical hand coordinate systems. This study confirms that, as accelerometers remain the major technology for vibration measurement, it is reasonable to standardize two types of coordinate systems: a tool-based basicentric (BC) system and an anatomically based biodynamic (BD) system. However, these coordinate systems are not well defined in the current standard. Definition of the standard BC system is confusing, and it can be interpreted differently; as a result, it has been inconsistently applied in various standards and studies. The standard hand BD system is defined using the orientation of the third metacarpal bone. It is neither convenient nor defined based on important biological or biodynamic features. This explains why it is rarely used in practice. To resolve these inconsistencies and deficiencies, we proposed a revised method for defining the realistic handle BC system and an alternative method for defining the hand BD system. A fingertip-based BD system for measuring the principal grip force is also proposed based on an important feature of the grip force confirmed in this study.

1. Introduction

Prolonged, intensive exposure to vibration may cause hand–arm vibration syndrome. Vibration direction is one of the important exposure factors [1]. This is not only because the vibration emission from any powered hand tool or machine is direction specific, but also because the biodynamic properties and biodynamic responses of the hand–arm system are direction specific [2–6]. Furthermore, the directional vibration input is correlated with the directional biodynamic responses [7]. As biodynamic responses are part of the mechanisms of the vibration effects [1,8], vibration-induced injuries and disorders are likely to be direction specific. While the psychophysical effects of vibration direction have been demonstrated in the results of some studies [9,10], little information on the effect of vibration direction on injuries and disorders is available. It is also very difficult to take vibration direction into account in risk assessments of vibration exposure, as vibration is actually transmitted to different parts of the hand simultaneously in various directions. The direction of vibration exposure may also vary with the postures of the hand and arm, time, tools, working condition, and individuals. Probably for these reasons, vibration direction has not been taken into account in the standard assessment method defined in International Organization for Standardization (ISO) 5349-1 [11]. The standard, however, generally requires measurement of the vibrations in three orthogonal directions using standard coordinate systems. Such coordinate systems are also

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required for the measurement of biodynamic responses and for the testing and evaluation of powered hand tools and antivibration devices [12–14].

As shown in Fig. 1 [11,15], the standard hand coordinate systems include a basicentric (BC) coordinate system and a biodynamic (BD) coordinate system [11]. They are originally defined in the initial version of ISO 5349 (1986) and their detailed definitions are included in ISO 8727 [15,16]. As the BC system is not clearly illustrated in ISO 8727, an amendment of this standard has recently been proposed to make its hand coordinate system figure fully consistent with that included in the latest version of ISO 5349-1 [11].

While Fig. 1 has been adopted in many books and national standards [17–22], the use of the standard coordinate systems has been claimed in many studies of vibration exposure and biodynamic responses [23–28]. However, the following observations cast doubt on the practical usefulness of these coordinate systems:

(1) The BC coordinate system shown in Fig. 1A seems to be inconsistent with that recommended in the standards for vibration measurement on the vast majority of tools [14,22,29]. While an effort has been made to approximately align the measurement coordinates with the standard BC coordinates [30], orientations of the accelerometers installed on many tools reported from many studies are unlikely to make their measurements consistent with that shown in Fig. 1A [2,3,26].

(2) The BC system defined in ISO 8727 is confusing: its written definitions of x and z coordinates are different from their illustrations in Fig. 1A. It is also different from that illustrated in a handbook on human vibration [1]. While the written definition of the x axis is in line with, or approximately along, the functional axis or action direction of a tool in ISO 8727, the action direction is generally assigned to the z axis of the tool-specific BC system in ISO 5349-2 [29]. In some cases, it is also assigned to the y axis of the BC system in the tool tests defined in ISO 28927 [14].

(3) The title of ISO 8727 is “Biodynamic Coordinate Systems,” but its hand BD system is rarely used in biodynamic measurements and analyses, although its use was claimed in some studies [27,28]. The standard BD system is consistent with that described in the handbook on human vibration [1], but it is different from those actually used for the measurement and analysis of biodynamic responses, and testing and evaluation of antivibration devices [3–6,31–37].

These large inconsistencies may be one of the reasons for the considerable differences between the reported experimental data of vibration exposures and biodynamic responses [25,31,38]. The inconsistencies may partially result from some misinterpretations or ignorance of the standard definitions. This study, however, hypothesizes that the major reason for the large inconsistencies is that the standard coordinate systems themselves are not well defined, or they are not convenient or suitable for their intended applications; as a result, alternative coordinate systems have to be defined and used in practical measurements and analyses.

Although these inconsistencies have been noticed for many years, the standard hand coordinate systems have not been revised since they were originally defined over 30 years ago. The recent amendment of ISO 8727 does not address these important issues. This may be because they have not been sufficiently recognized and understood, and/or their solutions have not been found. Besides some brief introductions [1,15], a comprehensive explanation of the principles behind the various definitions of the hand coordinate systems is not found in the literature. There is also the lack of a systematic evaluation of these hand coordinate systems.

If the relationships among various coordinate systems are determined or quantified, the experimental data measured in these systems can be transformed to a given coordinate system for comparison and analysis. While a preliminary laboratory study has examined the relationship between a wrist coordinate system and a handle coordinate system [36], little quantitative information on the relationships between the standard coordinate systems and alternative coordinate systems has been reported.

In order to help improve the standard hand coordinate systems and consistently apply them to further studies, this study performed a systematic review and evaluation of the hand–arm BC and BD coordinate systems for the measurements and analyses of hand-transmitted vibration exposures, biodynamic responses, and hand forces. The specific aims are as follows: (1) to further confirm

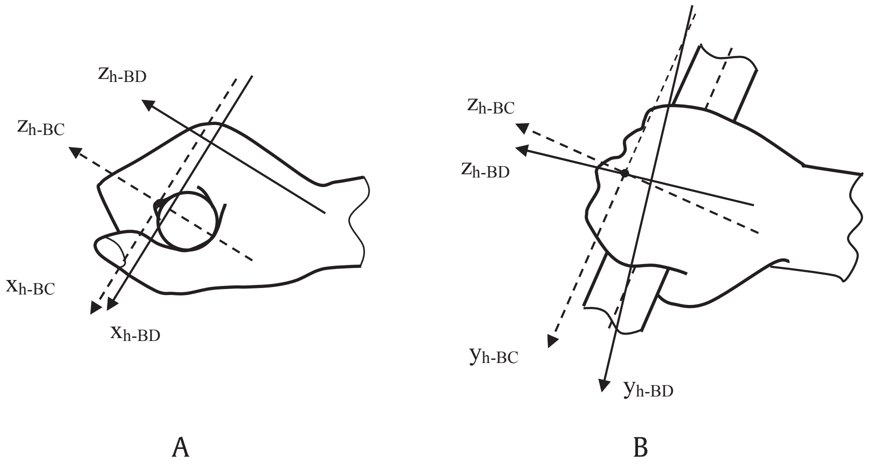

Fig. 1. Standard hand coordinate systems for grasping a cylindrical handle defined in ISO 5349-1 and ISO 8727 [11,15]. The BD system has its origin at the center of the head of the third metacarpal bone; the $z_{\text{h-BD}}$ axis is the long axis of the third metacarpal bone, and the $x_{\text{h-BD}}$ axis is approximately normal to the palm of the hand and perpendicular to the $z_{\text{h-BD}}$ axis. The $y_{\text{h-BD}}$ axis is perpendicular to the two axes. The BC system has its origin on the handle surface; its $z_{\text{h-BC}}$ axis is parallel to $z_{\text{h-BD}}$ in the x–z plane, and its $x_{\text{h-BC}}$ is parallel to $x_{\text{h-BD}}$, but its $y_{\text{h-BC}}$ axis is parallel to the handle axis. (A) Coordinate system in the x–z plane. (B) Coordinate systems in the y–z plane. BC, basicentric; BD, biodynamic; h-BC, hand basicentric; h-BD, hand biodynamic; ISO, International Organization for Standardization.

Fig. 2. Examples of tool operations and three coordinate systems. (A) Jack hammer used in repairing a road (Adapted from www.hsa.ie/eng/Topics/Physical_Agents/). (B) Rivet hammer used in repairing an air plane frame. The green dashed arrow (- - →) represents the *z* axis (tool action direction) of the tool coordinate system, blue dashed–dotted arrow (-·-·→) the *z* axis of an anatomical (forearm) coordinate system, and the blue dotted arrow (·····→) the *z* axis of a local skin coordinate system.

the consistency issues; (2) to clarify and enhance the understanding of the basic principles of the hand–arm coordinate systems; and (3) to apply the principles to evaluate typical hand–arm coordinate systems for identifying or defining more suitable BC and BD systems. For better evaluation, this study also measured the basic relationships among typical BD coordinate systems.

2. General principles and practices

Various coordinate systems have been created and used for different applications. Generally speaking, the defined or selected coordinate system should be as simple and convenient as possible for the purpose of measurement using a given technology. While a cylindrical coordinate system is convenient to study grip pressure and grip force [39–46], a Cartesian coordinate system is generally the simplest and most convenient system for vibration measurement and analysis; hence, it has been adopted as the standard coordinate system [11]. This type of a system has three linear axes or coordinates in mutually orthogonal directions that share a common origin. Once two axes are defined, the third one is automatically determined. Then, the primary concern becomes how to appropriately define or select the origin position and two essential axes of the coordinate system.

If it is practical, a global coordinate system fixed on the earth should be used for the required measurements and evaluations. Such a global system can reduce the uncertainty of a coordinate system orientation by using a known fixed reference, and helps avoid the mathematical transformation of coordinates in the measured data. Such a choice has been used widely to measure human motions in biomechanical studies [18,20]. While it may be feasible to use a global coordinate system to measure low-frequency vibrations, this approach has not been practical and reliable for measurements of vibration in the entire frequency range of concern (5–1,500 Hz) for hand-transmitted vibration exposure. The global coordinate system is the best choice for the measurement of vibration using a three-dimensional laser vibrometer [6,35]. While this expensive technology is applicable for vibration measurements on a stationary target in a laboratory experiment, it is not suitable for workplace measurements, as the tool and hand–arm system are typically not stationary during tool operations and it is very difficult for the laser beams to track the moving target.

Accelerometer technology remains the most convenient, affordable, and sufficiently reliable approach for the measurement of hand-transmitted vibration exposures, both at workplaces and in laboratories. It is thus the primary technology recommended in the standards for the measurement and assessment of human vibration exposures [11,47]. Consequently, definitions of the hand–arm coordinate systems should primarily be based on the application of this technology. Each accelerometer must be mounted at a certain location on a vibrating tool or a hand–arm system. This requires identifying a local coordinate system for the application of the accelerometer technology.

Fig. 2 shows two examples of tool operations at workplaces. The *z* axis of the local coordinate system at each of the four locations is plotted in the figure. These examples demonstrate that the local coordinate orientations vary with their locations and are generally not aligned with each other. Their relationships on the left hand may be different from those on the right hand. They also vary with the specific tools and some other factors such as time, individuals, and working condition. It would be extremely difficult if a single local coordinate system would be required to measure the vibrations distributed on the tools and hand–arm systems using the accelerometer technology. Multiple coordinate systems have to be considered for the measurements. This explains why the ISO standards define two types of coordinate systems. While the BC coordinate system is primarily defined for the measurement of the vibration input to the hand, the BD coordinate system is primarily defined for the measurement and analysis of biodynamic responses. Whenever necessary, the typical relationship between the BC and BD systems for each tool operation condition can be measured, and the experimental data measured in the BC system

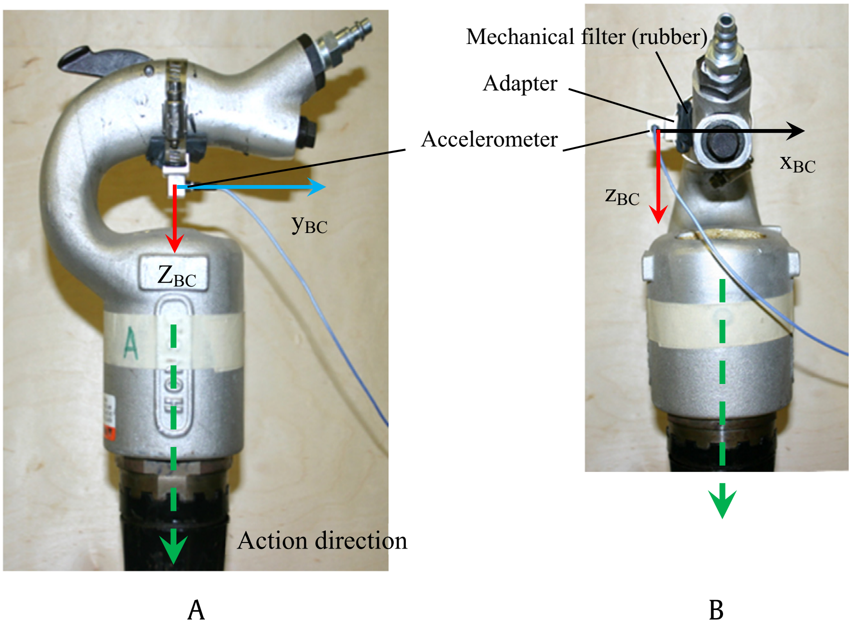

Fig. 3. Location and orientation of a triaxial accelerometer installed on a chipper hammer. (A) Recommended location. (B) Not recommended location. BC, basicentric.

can be mathematically transformed into the BD system for analyzing biodynamic responses. A study has implemented this strategy [48].

Measurement and analysis of the hand grip force also require both the BC and BD systems. This is because the force sensors used for the measurement are usually installed on a tool handle, but the loads in the bones, tissues, and joints required for studying health effects and performing risk assessment are generally predicted in a global or BD coordinate system. The specific principles and practices for defining the BC and BD systems are summarized and discussed in the following two sections.

3. BC coordinate system

3.1. *General objectives and definitions of the BC system*

As vibrations in the three orthogonal directions are considered equally important in the standard assessment method [11], the exact measurement direction is not critical when the standard method is used in risk assessments of hand-transmitted vibration exposures. However, the direction information is important for further studies of the health effects. The relationship between the BC and BD systems is important for measuring and analyzing biodynamic responses and for designing and analyzing powered hand tools and antivibration devices. For these reasons, the specific aims of the BC system are as follows: (1) to help ensure reliable measurements of the vibrations actually transmitted to the hand in three orthogonal directions, and (2) to help consistently measure vibration exposure on each type of tool to reduce the difficulties in describing and measuring the relationship between the BC and BD coordinate systems.

To achieve these aims, the BC system has usually been defined based on the structural/geometric features of each tool handle and the functional or action direction of the tool. The specific definitions of the BC system are summarized and discussed as follows:

(1) Translational position of the coordinate origin along a handle. To ensure that the measured vibration is representative of the input to the hand, the accelerometer should be installed at the center of the handle grasping area. While this is usually achieved by designing an instrumented handle primarily for laboratory experiments, the accelerometer is usually installed on the surface of a tool handle at a location as close to the center of the grip area as possible [29], provided that this is consistent with safe operation practice. The use of a fingers-held or a palm-held adapter can facilitate the measurement at the center area, without introducing substantial interference on some tools. The adapter may also be wrapped around the handle using an elastic material, to increase its stability and avoid dropping it during the tool operation. However, the hand-held adapter method, especially the fingers-held adapter method, is usually the least reliable among the four methods recommended for accelerometer installation [29,48–50]. The most reliable installation method is to install the accelerometer using a handle adapter firmly clamped on the handle, as shown in Fig. 3A. If the assembly cannot be installed in the grasping area, or if it may significantly affect the tool operation, it can be installed outside this area, but it should be close to the hand at the thumb or index finger end of the handle if applicable.

(2) Angular position of the coordinate origin around a handle. The origin of the BC system should generally be located on the handle surface plane that is perpendicular to the dominant vibration direction, as shown in Fig. 3A. An alternative installation location is shown in Fig. 3B. If possible, such an alternative choice should be avoided. This is because the accelerometer–adapter–filter assembly installed on the handle is effectively a cantilever-like structure with its foot on the handle surface. Such a structure may swing and substantially amplify the vibration in the frequency range of concern. This is especially important for the vibration measurement on impulsive tools such as chipping hammers and riveting hammers, as a mechanical filter is usually required to minimize the DC shift induced from shocks on such tools. The filter may significantly reduce the lateral resonant frequency of the assembly because the filter increases the length of the assembly and reduces its shear stiffness.

(3) Definition of y_{BC}. The y_{BC} axis can be defined easily whenever the handle has a cylindrical shape in the grip area. Consistent

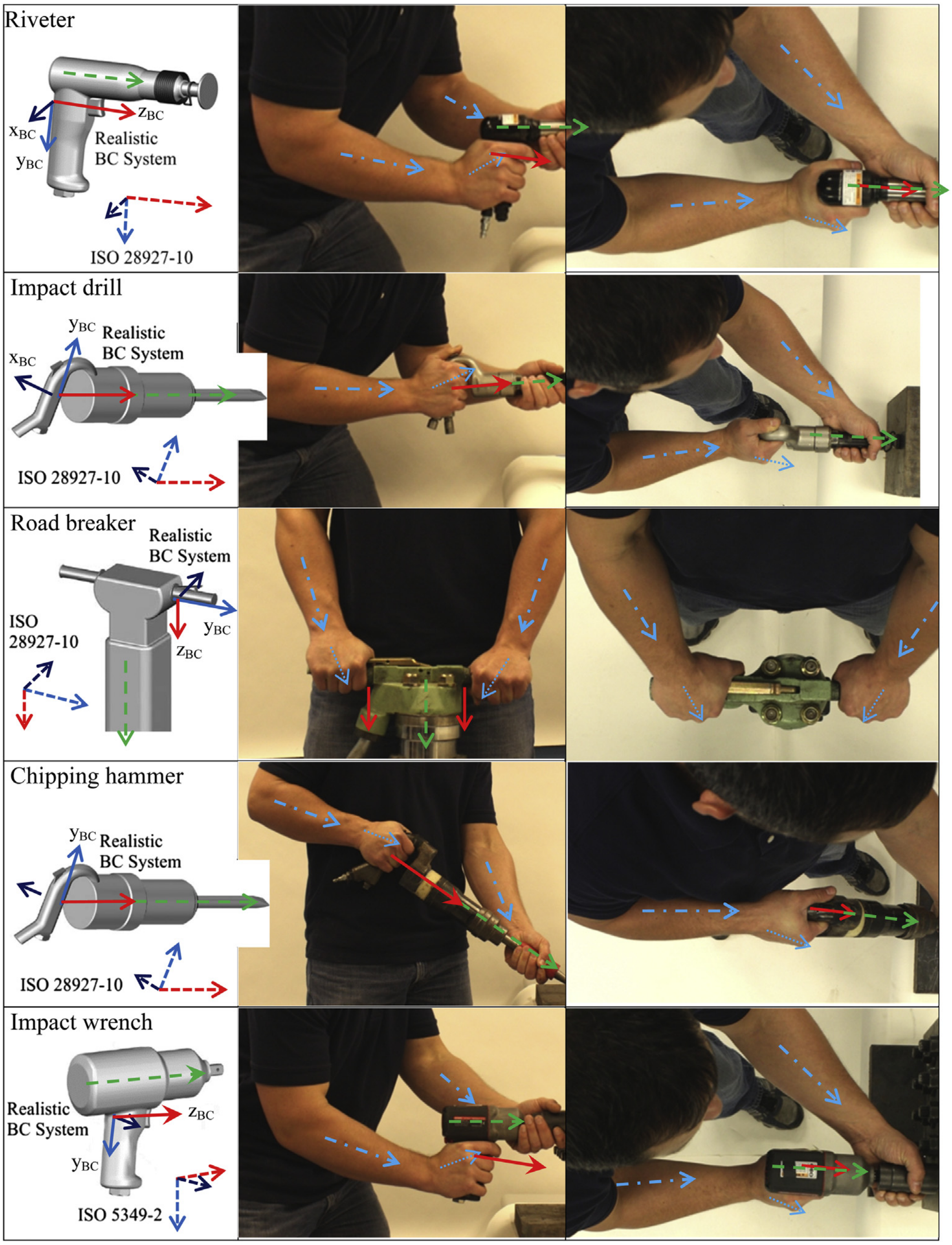

Fig. 4. Impulsive tools, their typical working postures, and coordinate systems. The green dashed arrow (- - -→) represents the tool action direction or major push/feed force direction, blue dashed–dotted arrow (-·-·→) the *z* direction of the anatomical (forearm) coordinate system, red arrow (——→) the z_{BC} direction of the realistic BC system, and the blue dotted arrow (·······→) the $z_{h\text{-}BD}$ direction of the standard BD system. BC, basicentric; BD, biodynamic.

with the definition used in some standards and studies [3,11,14,15,22,29], the y_{BC} axis is parallel or approximately parallel to the longitudinal axis of the handle in the grip area, as also shown in Figs. 1B, 3A. The accelerometer adapter should have a cylindrical or V-shaped contact surface to assure its stable attachment along the handle axis, so that unity transmissibility can be achieved in the entire frequency range of concern [48]. The y_{BC} axis defined in such a way also has some special biodynamic significance. As the shear stiffness of soft tissues is usually lower than their compression stiffness, the apparent mass along the axial direction of the handle is usually lowest among the three directions [5]. Partially for this reason, antivibration gloves are usually least effective in the handle axial direction [3,37]. In the axial direction, contact soft tissues are primarily subjected to shear deformation; its biological implications may be an interesting topic for further studies.

(4) Definition of z_{BC}. Inconsistent with the standard definition in ISO 8727 [15] but consistent with that actually used in other standards and studies [3,14,22,29], the z_{BC} axis is perpendicular to y_{BC} and parallel or approximately parallel to the functional or action direction of a tool, as shown in Figs. 1B, 3A. It is also approximately parallel to the forearm direction in the operation of some tools, as shown in Figs. 4–6. Some tool handles do not have a right angle (90°) relative to the action direction of the tool. Such a design takes into account the facts that the handle held by a hand is not naturally perpendicular to the

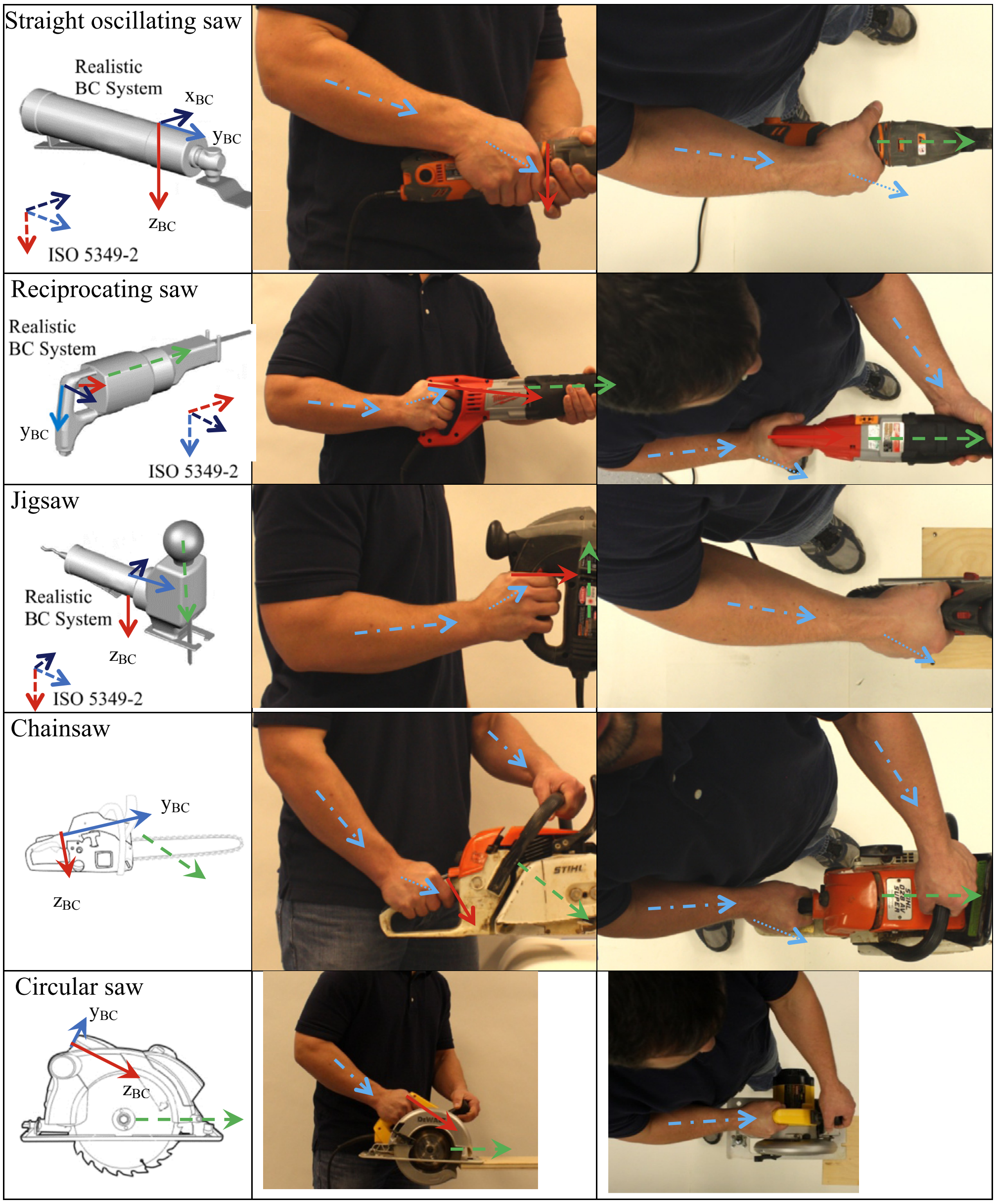

Fig. 5. Saws, their typical working postures, and coordinate systems. The green dashed arrow (- - -→) represents the tool action direction or major push/feed force direction, blue dashed–dotted arrow (-·-·→) the *z* direction of the anatomical (forearm) coordinate system, red arrow (——→) the z_{BC} direction of the realistic BC system, and the blue dotted arrow (······→) the $z_{h\text{-}BD}$ direction of the standard BD system. BC, basicentric; BD, biodynamic; h-BD, hand biodynamic.

forearm axis when the wrist is in a neutral position (0° tilting angle, and 0° bending or yaw angle), as shown in Fig. 1B, and that approximately aligning the forearm axis with the tool action direction can minimize the push effort or maximize the push force. However, alignment of the z_{BC} axis with the action direction on such tools may require the creation and use of a special accelerometer adapter. This not only is inconvenient, but also makes the y_{BC} axis misaligned with the long axis of the handle. It is also unnecessary to fully align the z_{BC} axis with the action direction when the vector sum of the three axial vibrations, without applying any direction weighting, is required to assess the vibration exposure using the standard method [11]. Therefore, it is better to use the natural orientation of the handle to define the realistic z_{BC} axis.

(5) Special cases. On some tools such as straight sand rammers and straight drills, the handle axis is in the same direction as the action direction of the tools. In such cases, the y_{BC} axis should still be assigned to this direction for the evaluation of shear deformation; the z_{BC} axis should be in the direction approximately parallel to the forearm axis. This is consistent with that used in ISO 28927 [14] and in the proposed amendment of ISO 5349-2 [29].

(6) Definition of x_{BC}. Following the requirements of a Cartesian coordinate system described previously, the x_{BC} axis is perpendicular to the y_{BC} and z_{BC} axes.

3.2. Evaluations of the BC coordinate systems used for vibration measurement

Based on the aforementioned BC definitions, the realistic BC systems for many tools are created and shown in the first column of

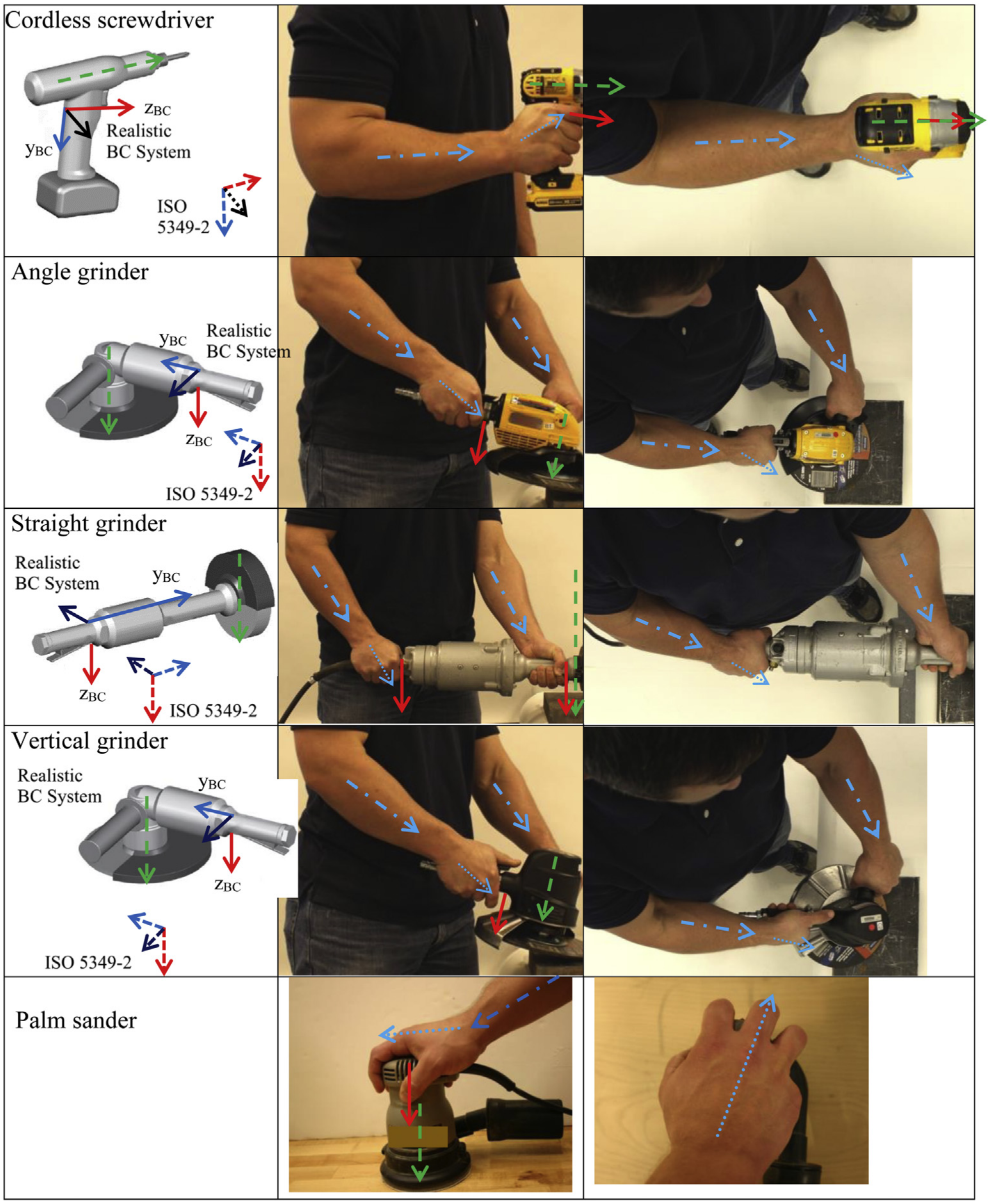

Fig. 6. Drills and grinders, their typical working postures, and coordinate systems. The green dashed arrow (- - -→) represents the tool action direction or major push/feed force direction, blue dashed–dotted arrow (-·-·→) the *z* direction of the anatomical (forearm) coordinate system, red arrow (——→) the z_{BC} direction of realistic BC system, and the blue dotted arrow (·······→) the $z_{h\text{-}BD}$ direction of the standard BD system. BC, basicentric; BD, biodynamic; h-BD, hand biodynamic.

Figs. 4–6. BC systems for many tools are also specified in the proposed revision of ISO 5349-2 [29]. They are consistent with those specified for the laboratory tool tests defined in ISO 28927 [14]. They are also shown in the first column of Figs. 4–6 for direct comparison. In most instances, they are clearly consistent with the realistic BC systems, except for the tools with non-right-angle handles. Such a disagreement is likely to be because the definitions of the BC systems specified in these tool test standards are influenced by the standard BC definition in ISO 8727 [15]. The standard BC coordinate axis along the tool action direction is defined first [15], making the action direction the primary reference for defining the BC system. The emphasis on the alignment is because the action direction is usually the dominant vibration direction, and only the vibration in the dominant direction is required to assess the exposure in the original version of ISO 5349 [16]. As mentioned above, such an alignment is neither convenient nor necessary for tools with non-right-angle handles when the triaxial method is required for the assessment of vibration using an accelerometer.

The x_{BC} axis is assigned to the tool action direction in ISO 8727 [15]. This is inconsistent with that used in ISO 5349-2 [29] and ISO 28927 [14]. The exchange of the x_{BC} and z_{BC} axes in these standards is probably because the tool action direction is usually assigned to the *z* axis used in the design and analysis of a tool. This exchange also makes the z_{BC} axis consistent with the z_{BD} axis used in the definitions of hand–arm biodynamic responses described in ISO 10068 [12].

As further demonstrated in Figs. 4–6 (2nd and 3rd columns), the tool action direction is similar to the forearm direction, except for a few tools such as palm sanders and orbital sanders. This may become more obvious when a forceful push is required, as it is a natural reaction to align the forearm with the push direction to achieve the maximum push force or to minimize the push effort. Probably for this reason, alignment, together with some other typical operation conditions, is simulated in the standard anti-vibration glove test [13]. Specifically, the standard glove test requires a 40 mm handle equipped with an accelerometer and force sensors to be fixed on a single-axis shaker in a vertical direction to deliver, measure, and control the vibration input to the hand, as well as to measure the grip force and/or push force. The forearm and push force are required to be in line with the direction of the vibration. The grip force is also measured along the single-axis vibration direction. The handle–hand–arm postures for the glove test are shown in Fig. 7A [15,22,42,51]. Such test conditions have also been used in the measurements of the driving-point biodynamic response of the hand–arm system and the vibration transmissibility distributed on the system [5,6,35–37]. They are also the desired test conditions for the measurement of the experimental data included in ISO 10068 [12,31,38]. Hence, these typical hand–arm postures and test conditions are considered as a common basis to further compare and evaluate the various coordinate systems.

The profile of the pictorial view of the hand–arm system shown in Fig. 7A is replicated and plotted in Fig. 7B, 7C. Such a real hand–handle coupling relationship is very similar to that shown in Fig. 1.

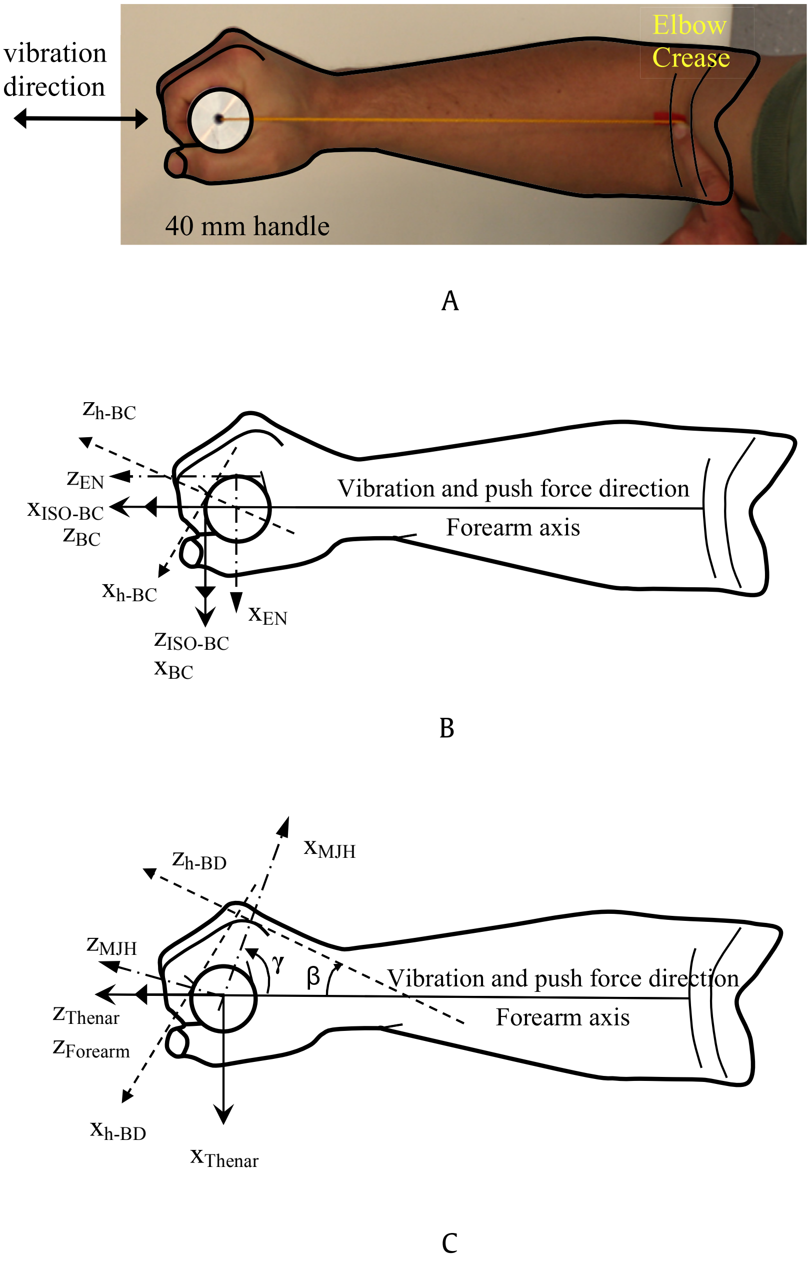

Fig. 7. Hand–arm system holding a 40-mm cylindrical handle. (A) Typical laboratory experimental conditions on a 1-D vibration test system. The handle is in the vertical direction, the hand with no bending angle grasps and pushes on the handle, and the forearm is aligned with the vibration in the horizontal direction. (B) BC coordinate systems. The h-BC system is that shown in Fig. 1; ISO-BC system is that we interpreted from the written description in ISO 8727 [15]; EN system is used in BS EN 60745 [22], and BC system is the realistic handle BC system. (C) BD coordinate systems. MJH system is used by Edgren et al [42], thenar system is a combined handle–hand system initially used by Dong et al [51], forearm system is an anatomical coordinate system of the forearm, and angles β and γ are used to characterize the relationships among the BD coordinate systems. BC, basicentric; BD, biodynamic; h-BC, hand basicentric; h-BD, hand biodynamic; MJH, metacarpal joint head; 1-D, one dimensional.

This suggests that their coupling relationship shown in the original ISO 5349-1 and ISO 8727 is reasonable, except that the handle in Fig. 1A should be represented using an ellipse if the handle shown in Fig. 1B is not in vertical direction. The similarity also justifies replicating the standard BC and BD systems Fig. 7B and Fig. 7C, respectively. Fig. 7B also includes an ISO-BC system, which is our interpretation of the written definition of the BC system in ISO 8727 [15]. The EN system used in BS EN 60745 [22] is also plotted in Fig. 7B, which is the same as the BC system recommended in the handbook written by Griffin [1]. The realistic handle BC system for the given test conditions in the x–z plane is also plotted in Fig. 7B. While the standard BC system (h-BC system) shown in Fig. 1 is obviously different from the realistic handle BC system, our interpreted ISO-BC system is consistent with it, except that the $x_{\text{ISO-BC}}$ and $z_{\text{ISO-BC}}$ are swapped because the x axis is assumed as the tool action direction in the text of ISO 8727 [15]. These observations suggest that the standard BC system shown in Fig. 1 is not correctly interpreted from its written definition. The EN system is basically consistent with the realistic handle BC system with the exception of its origin location. As discussed in the section *General objectives and definitions of the BC system*, the origin location of the EN system is not optimized if the action direction shown in Fig. 7 is the dominant vibration direction of a tool.

4. Biodynamic BD coordinate system

4.1. General objectives and principles of the BD system

When an accelerometer is used to measure the vibration transmitted to the hand–arm system of a living individual, the accelerometer is usually attached to the skin. The deformable feature of the skin and the mass effects of the accelerometer and adapter make it difficult to accurately measure the responses on the skin using an accelerometer [36]. Furthermore, the vibration measured at one or few points on the skin may not fully represent the vibration exposure of the entire substructure. For these reasons, the standard method for risk assessments of hand-transmitted vibration exposures is not based on the measurement of the transmitted vibration [11]. Vibration transmissibility spectra measured on the skin at various locations on the hand–arm system, together with the biodynamic response functions measured at the hand–tool interface, are primarily used to help understand the motion mechanisms of the hand–arm system, develop computer models and alternative frequency weightings for risk assessment, and design and evaluate tools and antivibration devices. Therefore, the specific aims of the BD coordinate systems are to help consistently measure, report, and analyze the biodynamic responses and to help describe and measure the postures of the hand–arm system.

ISO 8727 requires any BD coordinate system to be precise and bony anatomy-based [15]. This is reasonable for whole-body vibration studies. It is also partially correct for hand–arm vibration studies, as the vibration is likely to be primarily transmitted through bones and joints. This requirement, however, overestimates the importance of the bony structures and makes such defined BD coordinate systems inconvenient for the following reasons: (1) unlike the whole-body skeletal system, visible bony locations on the hand–arm system are not symmetrically distributed; (2) unlike the whole-body vibration exposure, none of the visual hand bone axes are generally aligned with the BC coordinates of the tools, as shown in Figs. 4–6; and (3) while the major concerns with regard to whole-body vibration exposure are injuries or disorders of the spine where the coordinate system is defined, the major concerns of hand–arm vibration exposure are injuries and disorders of soft tissues. Furthermore, it is not necessary to require a precise BD system for the following reasons: (1) mathematically, if the deviation (ψ) of an accelerometer coordinate from its ideal position is controlled to within 15°, the percent difference $[= (1 - \cos(\psi)) \times 100]$ is $< 4\%$, which is not critical for practical engineering applications; and (2) as many factors can influence the vibration exposure and biodynamic responses, intrasubject variation is usually controlled at $\leq$ 15% and intersubject variations are usually larger, even if the measurements are conducted in well-controlled laboratory experiments [2,5,6,19]. Probably, partially for these reasons, the standards on antivibration glove testing and tool tests specify the postures of the hand and arm, but they do not specify how to measure and control them [13,14]; they are practically controlled by visual observations or crude measurements [2,52]. Similar practices have also been applied to the measurement of biodynamic responses and glove transmissibility [5,34,35,37]. For ergonomic assessments, hand–arm postures observed at workplaces are also primarily quantified visually. Even if a precise bony anatomy-based BD coordinate system can be defined based on a radiograph of the hand–arm skeletal structure, it is not feasible to precisely implement such a system on humans in vibration experiments.

Based on the above discussions and the features of the hand–arm vibration exposure and health effects, the major principles and criteria of the BD coordinate systems for hand–arm vibration experiments are proposed as follows: they should have acceptable accuracy for practical engineering applications; they are visually identifiable, practically convenient, easily implementable for the measurement of biodynamic responses to study soft tissue injuries and disorders, and as consistent as possible with the majority of the handle BC coordinate system. The bony anatomy-based approach adopted in the standard is actually not a fundamental principle that is generally applicable; it is simply one of the tactics that can be used to implement the general principles. This tactic is useful when transmissibility on a hard tissue is of interest.

4.2. Definitions of the BD coordinate systems

These BD systems can broadly be classified into three categories: (1) bony anatomical structure-based coordinate systems; (2) skin coordinate systems; and (3) combined handle–hand coordinate systems. The first anatomical coordinate system is defined primarily based on the longitudinal axis of the bony anatomy of interest. It is similar to that used in the studies of human motions and biomechanical loads [18,20]. For example, the standard BD system shown in Fig. 1 is a typical bony anatomical coordinate system. While the forearm has two bones, the baseline coordinate (z_{Forearm}) of the forearm in the x–z plane shown in Fig. 7C can be defined using the method shown in Fig. 7A: it is along the line connecting the center of the handle and the middle point of the crease in the elbow area, as the hand tightly grips the handle with a neutral wrist posture. Although the middle point cannot be located accurately using any bony landmark, the potential error induced from the possible uncertainty is unlikely to be greater than that in the use of the standard BD system. This is because the line for defining the z_{Forearm} axis is much longer than the possible offset from the ideal middle point on the crease line.

As the origin of a bony anatomical coordinate system is usually on or inside a bone, it is not feasible to directly use such a system as a reference to install an accelerometer for the measurement of the transmitted vibration on the hand–arm system of a living individual. It is usually used to measure and describe the posture and motion of the system. A skin coordinate system is actually used to measure the transmitted vibration [36,53,54]. Such a coordinate system depends largely on the surface geometry at the selected location for the measurement. As vibration transmissibility is usually used to represent the overall motion of a substructure, the origin of a skin coordinate system for accelerometer installation should be selected at a representative location of the substructure [7]. Consistent with the bony anatomy principle adopted in ISO 8727 [15], it is conventionally assumed that the bone vibration is representative, and the transmissibility should be measured at a bony area of the substructure by tightly attaching an accelerometer to the skin of the bony protuberance. Recent studies have revealed that this assumption is not fully valid [7,36]. This is because the mass of the bone usually accounts for $< 20\%$ of the total mass of a substructure and bone vibration cannot fully represent the vibration of the entire substructure [18]. A study has also demonstrated that the transmissibility measured on a nonbony area on the upper arm is more correlated with the apparent mass measured at the palm of the hand [36], which further suggests that the soft tissue response of this substructure plays a dominant role in determining the overall transmissibility of the substructures. Furthermore, it is difficult to find a bony area on some substructures; it is also difficult to tightly fix an accelerometer or its adapter on an individual's skin without causing pain or discomfort, as a reliable tight fixture can impede normal blood circulation in the hand–arm system. These observations suggest that, whenever applicable and practical, transmissibility should be measured on both bony and nonbony areas of a substructure to synthesize the representative transmissibility [7]. This requires defining multiple skin coordinate systems and determining their relationships with respect to a global coordinate system.

To directly use the transmissibility data to conduct biodynamic analyses without the need for coordinate transformation, the z_{BD} axis of a skin BD system can be defined as the axis as close as possible to the z_{BC} axis of the realistic handle BC system. If the measured skin transmissibility is used to represent the response of the substructure in its anatomical coordinate system, the skin z_{BD} axis should be defined as the axis as close as possible to the z axis of the substructure BD system. Similarly, the other axes of the skin BD system can be defined. However, the definition of the skin BD system is constrained by the local skin geometry, as the accelerometer or its adapter must adapt to the local skin geometry. For example, the three-dimensional wrist transmissibility spectra can be measured by mounting an adapter equipped with a triaxial accelerometer on the wrist [36]. While the z axis of the adapter attached to the wrist skin can be approximately aligned with the z axis of the realistic handle BC system, the other two axes of the adapter are usually not aligned with those of the realistic handle BC system under the conventional test conditions shown in Fig. 7 [36]. Exact orientation of the adapter may also depend on the fastening force applied on it.

The combined handle–hand coordinate systems have not previously been fully defined, but they have been partially used in many studies [37,42,46,51,52,55]. Its full definition is proposed in this study, which is described and discussed in the section *Evaluation of combined handle–hand BD systems*.

4.3. Evaluation of the standard BD system

As shown in Fig. 1, the standard hand BD system (h-BD system) is defined based on the head and long axis of the third metacarpal bone [15]. Once a hand is coupled to a handle without significant relative movement, the relationship between this standard BD system and the handle BC system is unlikely to change significantly with the postures of the wrist, arms, and shoulder. As found in this study and presented in the section *Angular relationships among three BD coordinate systems*, the relationship between the standard BD system and thenar region-based BD system does not change substantially with the handle size. These features make the standard BD system an acceptable reference for describing hand postures and quantifying the relationship between a hand and a tool handle. This standard BD system may also be directly used as a local reference to measure the vibration transmitted to the dorsum of the hand. However, usefulness of the standard BD system is limited for the following reasons:

(1) The standard hand BD system has no obvious biological significance. No apparent evidence has shown that the third metacarpal bone is an essential substructure associated with the major components of the hand–arm vibration syndrome.

(2) It has no special biodynamic significance. Biodynamic responses of this metacarpal bone or those measured on the hand dorsum are not generally representative of those observed on any other substructure such as fingers, wrist, forearm, upper arm, and shoulder [6]; the principal driving-point biodynamic response is along the forearm direction [5]; although the $z_{h\text{-}BD}$ axis of the standard BD system is approximately along the forearm axis in the y–z plane, as shown in Fig. 1B, it is substantially different from that of the forearm BD in the x–z plane, as shown in Fig. 7C.

(3) The standard hand BD system has no special relationship with the BC system of the handles for the vast majority of tools. Except for a few tools such as palm sanders and orbital sanders, none of the three axes of the standard hand BD system is approximately in line with the action or feed force direction of the vast majority of tools, as shown in Figs. 4–7. The parallel relationship between the standard BC and standard BD systems shown in Fig. 1 does not generally exist.

4.4. Evaluation of combined handle–hand BD systems

A combined handle–hand coordinate system can be defined by utilizing unique geometrical features of a tool handle and the hand. The thenar region-based BD system is a typical combined handle–hand BD system. It was originally used by Dong et al [51]. Its full definitions are shown in Fig. 8 and described as follows: (1) the origin is located at the handle center in the grip area; it is at the head of the third metacarpal in the handle axial direction; (2) the z_{Thenar} axis is parallel to the forearm axis when the wrist is at fully neutral position (0° tilting angle and 0° bending or yaw angle); (3) the y_{Thenar} axis is in the plane formed by the handle axis (y_{BC}) and the z_{Thenar} axis, and is perpendicular to z_{Thenar}; and (4) the x_{Thenar} axis crosses the origin and is perpendicular to y_{Thenar} and z_{Thenar}.

The z_{Thenar} axis can be implemented by aligning a line drawn in the thenar region of the hand with one drawn on the handle [51], as shown in Fig. 9. As verified in this study, the marked line in the thenar region is always in line with the forearm axis when the wrist is kept at its neutral position, regardless of the handle size, as shown in the left column of Fig. 8. This supports the intuition that the thenar region-based BD system is independent of the handle size. This study also observed that the alignment of line markers on the hand and handle shown in Fig. 9 does not change with the postures of the wrist, forearm, and upper arm. This means that the thenar region-based BD system has a fixed relationship with the handle or its BC system. This feature is very important for quantifying the handle–hand relationships.

The natural angle between y_{BC} and y_{Thenar} with the neutral wrist posture was observed to be about 20°, as shown in Fig. 8. It is similar to the angular position of the non-right-angle handle on some tools shown in Figs. 4–6. This supports the design of non-right-angle handles on tools. The z_{Thenar} axis of the thenar region-based BD system is also approximately in line with the action direction of such tools in both the x–z plane and the y–z plane. Fig. 8 also suggests that the handle–hand relationship shown in Fig. 1B is

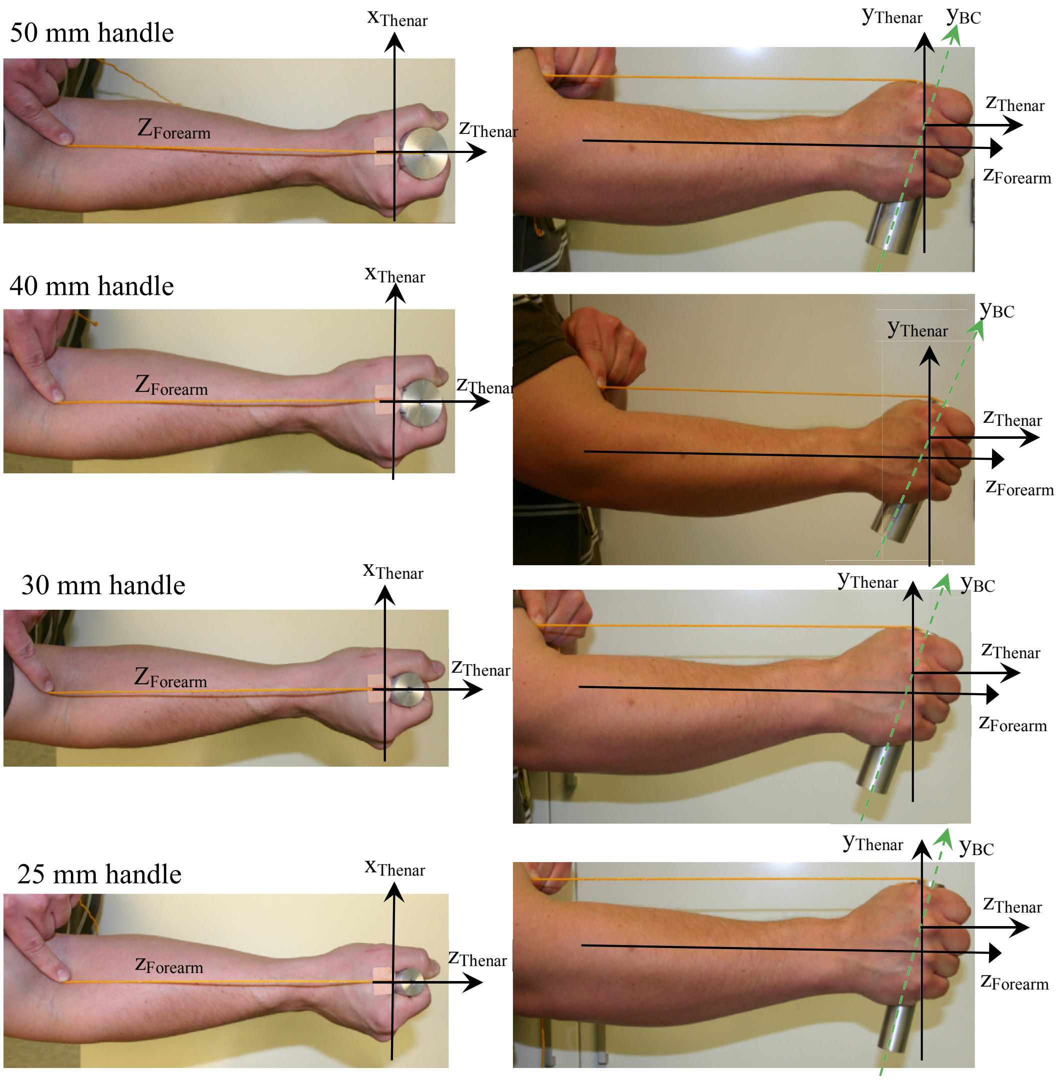

Fig. 8. Definition of thenar region-based hand biodynamic coordinate system, with the hand grasping a cylindrical handle and the wrist at its neutral posture.

reasonable. While the z axis of the standard BD system is approximately in line with that of the thenar region-based BD system in the y–z plane, there are large differences in the x–z plane.

When the handle is vertically fixed on a vibration test system in a laboratory and the forearm is controlled to be horizontal, the wrist of an individual has to tilt by about 20° in the y–z plane or they must change the grip posture in order to keep the conventional arm posture in the experiment. Therefore, the wrist is unlikely to be at the neutral position in the y–z plane under the abovementioned conventional laboratory test conditions, as shown in Fig. 7A. This, however, does not affect the definition and implementation of the thenar region-based BD system in the laboratory experiments using conventional test conditions, as such a BD system is independent of the wrist posture once it is defined and marked on the hand under the neutral wrist position. Under conventional test conditions, the thenar region-based BD system is fully consistent with the handle BC system, as shown in Fig. 7B, 7C. This is a unique and useful feature of this BD system.

Fig. 7C also includes another combined handle–hand coordinate system defined and used by Edgren et al [42]. It is similar to the thenar region-based BD system, except that its reference on the hand is at the metacarpal joint head (MJH). As confirmed in the following section, the MJH system is influenced by handle size, which introduces an additional variable to determine the relationship between the BD and BC systems. Furthermore, as shown in Fig. 7C, the MJH system is not aligned with the vibration direction under conventional laboratory test conditions. As confirmed in the following section, this system is not aligned with the principal grip direction. These observations suggest that the MJH system is unlikely to be more convenient or useful than the thenar region-based BD system.

5. Angular relationships among three BD coordinate systems

To further confirm the visual observations of the BD systems presented in the last section and to determine the relationships among the three systems shown in Fig. 7C, this study measured two angles (β and γ) in the x–z plane shown in the figure.

5.1. Experiment and results

Twenty adult persons (10 females and 10 males) participated in the experiment. None of them had previously experienced any upper extremity injuries. The measurement was performed on both

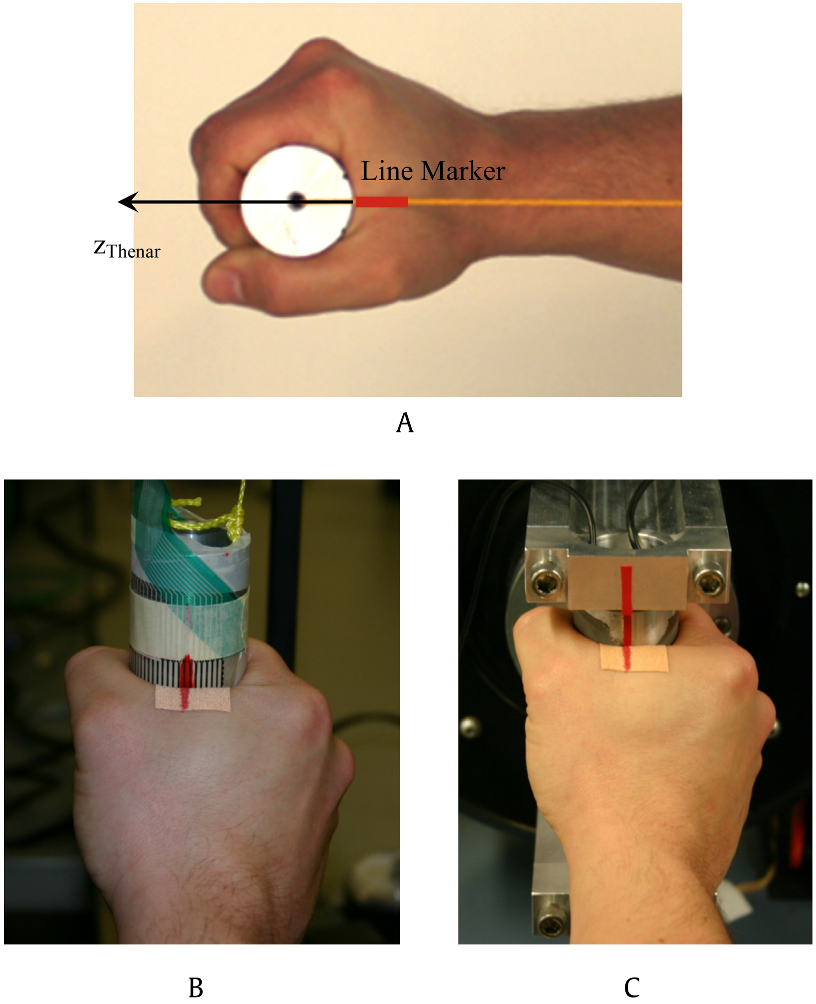

Fig. 9. Implementation of thenar region-based biodynamic coordinate system. (A) Line marker in the thenar region. (B) Measurement of grip pressure. (C) Measurement of biodynamic response.

hands of each participant. In addition to β and γ angles, hand length, width, and thickness were also measured. Six aluminum cylindrical handles (25 mm, 30 mm, 40 mm, 50 mm, 60 mm, and 70 mm) were made and used in the measurement to investigate the effect of handle size on the relationships. Similar to that shown in Fig. 7A, a string was used to determine z_{Thenar} or $z_{Forearm}$. According to the definition of $z_{Forearm}$, one end of the string was fixed at the handle center and the other end was located at the middle point of the first crease in the elbow area. The participant was advised to tightly grip the handle with a neutral wrist posture. The string was pulled and held tightly during the measurement. A protractor was used to measure the β and γ angles for each handle, according to their definitions shown in Fig. 7C. Two trials were made for each measurement condition.

Table 1 lists some anthropometric values for the 20 participants and the β and γ angles when they held the 40 mm handle, together with their means and standard derivations. Table 2 lists the average angles measured on the left and right hands of female and male participants for all the tested handles. A general linear model was used to perform the analysis of variance to determine the significance of influencing factors, in which the average length of the left and right hands for each participant listed in Table 1 was used as a covariate. The results indicate that the angular relationships (β and γ angles) measured on the left hand are not significantly different from those measured on the right hand ($F \leq 1.56$, $p \geq 0.212$). Although the analysis of variance results suggest that gender can be considered as a significant factor for both ($F \geq 6.04$, $p \leq 0.015$), gender difference did not substantially affect the angular relationships of the vast majority of cases, as shown in Table 2. As also shown in Table 2, increasing the handle diameter generally reduces the γ angle but increases the β angle ($F \geq 26.18$, $p < 0.001$). While these two angles are reliably correlated ($r = 0.66$, $p < 0.001$), variation range of the β angle (23.7–33.8°) is much smaller than that of the γ angle (83.0–50.2°).

Fig. 10 shows the average relationships among the three BD systems on the most frequently used handle sizes (30–50 mm) [11,42,51]. On average, the β angle changed only by 4° on these handles, which suggests that the third metacarpal bone-based BD system has an approximately constant relationship with the thenar region-based BD system. The direction of the principal grip force (F_{Max}) for each handle is also plotted in the figure, which was estimated in our previous studies [43,51,56]. Obviously, the principal direction varies with handle size, but it is correlated with the index fingertip location on the handle. This is because the peak grip pressure on a cylindrical handle is generally distributed in this area [43]. Therefore, the line connecting the middle point on the index fingertip and the handle center can be used as a coordinate reference for measuring the maximum or principal grip force. This

Table 1
Participant anthropometry and angular relationships among the three biodynamic coordinate systems on the 40 mm cylindrical handle

Participant ID	Gender	Body mass (kg)	Height (m)	Hand length (mm)	β (°)		γ (°)	
					Left hand	Right hand	Left hand	Right hand
2	F	56.7	1.60	179	28.2	31.3	80.1	76.7
3	F	70.3	1.68	178	29.9	26.6	73.2	76.9
5	F	72.5	1.72	172	31.1	28.0	64.2	74.1
7	F	54.7	1.60	173	37.6	33.4	60.8	56.9
9	F	52.0	1.63	181	24.3	23.7	71.6	74.9
11	F	59.0	1.68	173	23.8	24.7	69.0	68.7
12	F	54.4	1.61	176	22.1	28.1	66.5	70.4
13	F	58.9	1.68	172	27.1	31.3	79.2	80.1
15	F	54.4	1.62	166	31.9	28.2	65.0	70.6
19	F	49.9	1.67	173	24.5	23.0	68.5	70.6
Female mean		58.3	1.65	174	28.1	27.8	69.8	72.0
Female STD		7.1	0.04	4	4.5	3.3	6.0	6.1
1	M	86.2	1.83	185	27.6	25.0	63.9	62.5
4	M	74.8	1.79	182	29.6	28.2	58.5	67.6
6	M	102.1	1.84	195	25.9	22.9	72.8	79.0
8	M	74.8	1.75	188	27.9	30.3	67.8	73.8
10	M	102.2	1.73	186	30.4	27.1	70.0	67.0
14	M	79.4	1.75	193	27.6	27.9	69.7	76.2
16	M	88.5	1.85	195	31.4	37.0	63.6	62.2
17	M	61.3	1.61	182	29.1	30.8	73.7	74.8
18	M	75.4	1.75	192	29.1	30.8	73.7	74.8
20	M	65.0	1.70	174	31.3	33.5	63.0	57.2
Male mean		81.0	1.76	187	29.0	29.4	67.7	69.5
Male STD		13.2	0.07	6	1.7	3.9	5.0	6.9

F, female, M, male; STD, standard derivation.

finding contradicts the following assertion made in ISO 15230 [39]: “when the operator is gripping a cylindrical handle, the direction of the main gripping force is generally parallel to the z axis defined in ISO 8727.” It may be revised as follows: when the operator is gripping a cylindrical handle, direction of the main gripping force is approximately along the line connecting the index fingertip middle point and the handle center.

6. Summary and conclusion

A systematical review and evaluation of the hand–arm coordinate systems for measuring and analyzing vibration exposure, biodynamic responses, and hand forces were performed in this study. The basic principles and methods for defining these coordinate systems were clarified and further understood. This understanding supports the standardization of the following two types of coordinate systems: the BC coordinate system is primarily defined for guiding the installation of an accelerometer on a handle to measure the vibration exposure, and the BD coordinate system is defined primarily for describing, measuring, and analyzing the

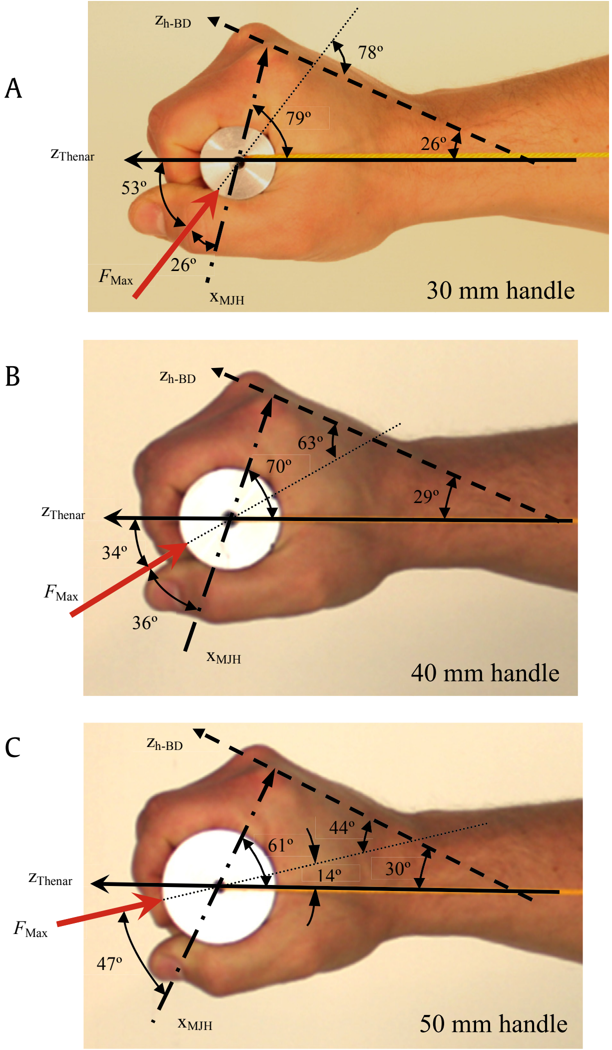

Fig. 10. Relationships among three BD coordinate systems of a hand holding cylindrical handles (30 mm, 40 mm, and 50 mm) and the principal/maximum grip direction in the three systems: $z_{h\text{-}BD}$—the standard hand BD system [11]; z_{Thenar}—the thenar region-based BD system [51], and z_{MJH}—the coordinate system based on the MJH of the index finger [42]. BD, biodynamic; h-BD, hand biodynamic; MJH, metacarpal joint head.

Table 2
Average angular relationships on seven handles

Gender	β angle (°)											
	25 mm		30 mm		40 mm		50 mm		60 mm		70 mm	
	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand	Left hand	Right hand
F	25.9	25.3	26.3	24.3	28.1	27.8	29.6	28.9	29.9	28.5	30.4	31.1
M	25.6	23.7	25.8	25.8	29.0	29.4	31.2	31.9	32.5	32.9	33.8	32.4
F–M difference (%)	1.4	6.6	1.8	6.1	3.3	5.3	5.2	9.9	8.5	14.3	10.5	4.2
Gender	γ angle (degree)											
	25 mm		30 mm		40 mm		50 mm		60 mm		70 mm	
F	80.6	83.0	79.0	80.1	69.8	72.0	61.5	63.0	54.4	56.0	52.1	52.1
M	82.5	82.8	77.9	79.1	67.7	69.5	59.5	61.0	52.8	53.8	50.2	50.6
F–M difference (%)	2.3	0.3	1.4	1.3	3.1	3.5	3.2	3.2	2.8	4.0	3.8	3.0

F, female, M, male.

hand–arm postures and biodynamic responses of the hand–arm system. Their general principles, as clarified in this study, are as follows: (1) the coordinate systems should be easily visually identifiable, conveniently implementable, and technically reliable for measuring vibration exposure, biodynamic responses, and hand forces; and (2) they should be as convenient as possible for measuring or estimating the relationships between various BC and BD systems such that the experimental data measured in different systems can be transformed for direct comparisons and analyses with minimal efforts; in other words, the BC and BD systems should be defined such that at least some of their coordinates are approximately aligned with each other under some operation conditions and/or in laboratory experiments.

Without clearly describing these general principles, the international standard requires the BD coordinate systems to be precisely defined based on bony anatomy, as stated in its introduction [15]. The requirement is actually a technical tactic for effectively implementing the general principles to define some BD coordinate systems. Unfortunately, this tactic is inappropriately treated as the fundamental principle/criterion that overrides the above-described general principles in the definitions of all the BD coordinate systems in the standard. While this tactic is acceptable for defining a BD system for measuring bone and joint responses, it is not fully suitable for hand–arm vibration studies. This is primarily because, unlike the human whole body, skeleton of the hand–arm system is not symmetrical; orientations of the tool handle coordinates are not naturally aligned with those of any visually recognizable bone landmark in the hand–arm system in the general vibration exposure; and the handle–hand relationship may vary greatly with tools, left and right hands, working pieces, individuals, and exposure duration. These characteristics indicate that it is neither necessary nor convenient to define and implement a precise bony anatomy-based coordinate system for measuring hand-transmitted vibration exposure, biodynamic responses, and related hand forces.

This review also confirms that multiple BD coordinate systems are generally required in hand–arm vibration studies, but only one BD system is defined in the standard to represent the hand coordinate system. It is basically defined according to the orientation of the third metacarpal bone. This bone does not have any unique biological significance in the vibration effects. The principle biodynamic response is not generally along its axis. More critically, orientation of this bone is not naturally aligned with the tool handle orientation. Therefore, it is neither meaningful nor convenient to use such a BD system to represent the hand coordinate system in hand-transmitted vibration exposure studies, which explains why it has rarely been used in practice. By contrast, the thenar region-based BD system is defined based on the general principles. Its convenience and reliability have also been tested in some studies [55,56]. It is also anticipated that the thenar region-based BD system can serve as a bridge between the tool-specific BC system and other hand–arm BD systems to determine their relationships, which may be useful for further studying the effects of postures on vibration health effects. These observations suggest that the thenar region-based BD system may be considered a candidate for the replacement of the hand BD system in the current standard if only one BD system can be included in the standard. The results of this study also confirm that the principal direction of grip force on cylindrical handles is approximately correlated with the index fingertip location on cylindrical handles. When the principal grip force is of concern, the index fingertip-based coordinate system can be considered to perform the measurement.

This study also found that the use of the unsuitable bony anatomy principle in the standard does not significantly affect the definition of the standard BC system. However, the BC system defined in the standard is confusing and can be interpreted differently. As a result, inconsistent BC systems were used in many application standards and studies. Based on the above-described general principles, some revisions are proposed to improve the definition of the standard BC system. Different from the standard approach, the proposed revisions use the longitudinal axis of a handle as the first reference and the action direction of a tool as the secondary reference to define the BC system.

Conflicts of interest

All authors declare no conflicts of interest. The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health.

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