Vicair & ISO 16840 tests conducted by Pittsburgh University

Introduction

This document highlights the importance of ISO tests, providing an explanation of the different tests, their clinical relevance, and how they are conducted. It also presents the test results for the Vicair Vector O2 and Adjuster O2 cushions, alongside comparisons with a reference foam cushion and an interconnected aircell cushion, shown in the included graphs.

The document begins with an explanation of the ISO tests for skin protection, followed by stability tests, and concludes with additional tests such as 10% force deflection and hysteresis. By the end, you will have a thorough understanding of why Vicair wheelchair cushions are a reliable choice, based on ISO tests conducted by an independent testing institute.

How to quantify a wheelchair cushion's performance? And which physical characteristics of a cushion are important?

To answer these questions, independent tests performed at Pittsburgh University with the Vicair cushions have been conducted, along with the Vicair cushions Pittsburgh University tested a cohort of 50 commercially available wheelchair cushions. These tests are based on the ISO 16840 standards for wheelchair seating. To understand the results of these tests, we want to give you some background information. ISO 16840 standards have been developed to compare physical characteristics of different wheelchair cushions. For this reason, test protocols have been developed so tests can be conducted in a standardized manner.

During the development of the ISO standards, the guidelines for the prevention and treatment of pressure Ulcers/Injuries provided by the National Pressure Injury Advisory Panel (NPIAP), European Pressure Ulcer Advisory Panel (EPUAP), and the Pan Pacific Pressure Injury Alliance (PPPIA) (European Pressure Ulcer Advisory Panel et al., 2019) have been considered. These guidelines provide direction on best practices in clinical practice, the aetiology of pressure injuries, scientific literature, and expert opinions. There are multiple factors that can contribute to a better understanding of cushion performance, factors that can be measured in a laboratory setting and play a role in the development of pressure injuries. These factors are pressure (immersion, envelopment, contact area), friction and microclimate. Vicair also published a literature synthesis about the importance of skin protection and associated factors (N. F. L. Conijn et al., 2024).

Skin protection

Due to the importance of the skin protective properties of a cushion, we will begin by explaining the standards that test for properties that can directly linked to skin protection.

There are a total of 5 skin protection tests that were conducted by Pittsburgh University on our cushions:

- **Loaded contour depth (immersion)** (ISO-16840-6:2015) (The International Organization for Standardization (ISO), 2015)
- **Envelopment immersion** (ISO-16840-12:2021) (The International Organization for Standardization (ISO), 2021)
- **Envelopment – Offloading** (ISO-16840-6:2015) (The International Organization for Standardization (ISO), 2015)
- **Contact area** (pressure mapping) (ISO-16840-9:2015) (The International Organisation for Standardization (ISO), 2015)
- **Dispersion index (pressure mapping)** (ISO-16840-9:2015) (The International Organisation for Standardization (ISO), 2015)

We will address each of these tests one by one, but first, how to interpret the results? We will address each of these tests one by one, but first, how to interpret the results?

Interpretation of the results

All ISO tests are repeated 3-5 times, with the displayed results representing the averages of these trials. To facilitate interpretation, a Bell curve (assuming a Normal/Gaussian distribution) is generated from each test, based on the 50 tested cushions by Pittsburgh University.

Based on the results of the whole tested cohort there are 3 categories created, which are based on the interquartile ranges within the Bell curve:

1. **Lower priority category, cushions with results that fall in the 0-25% category, Quartile 1.**
2. **Typical priority category, cushions with results that fall in the 25-75% category, Quartile 2+3.**
3. **Higher priority category, cushions with results that fall in the highest 25% (75-100%), Quartile 4.**

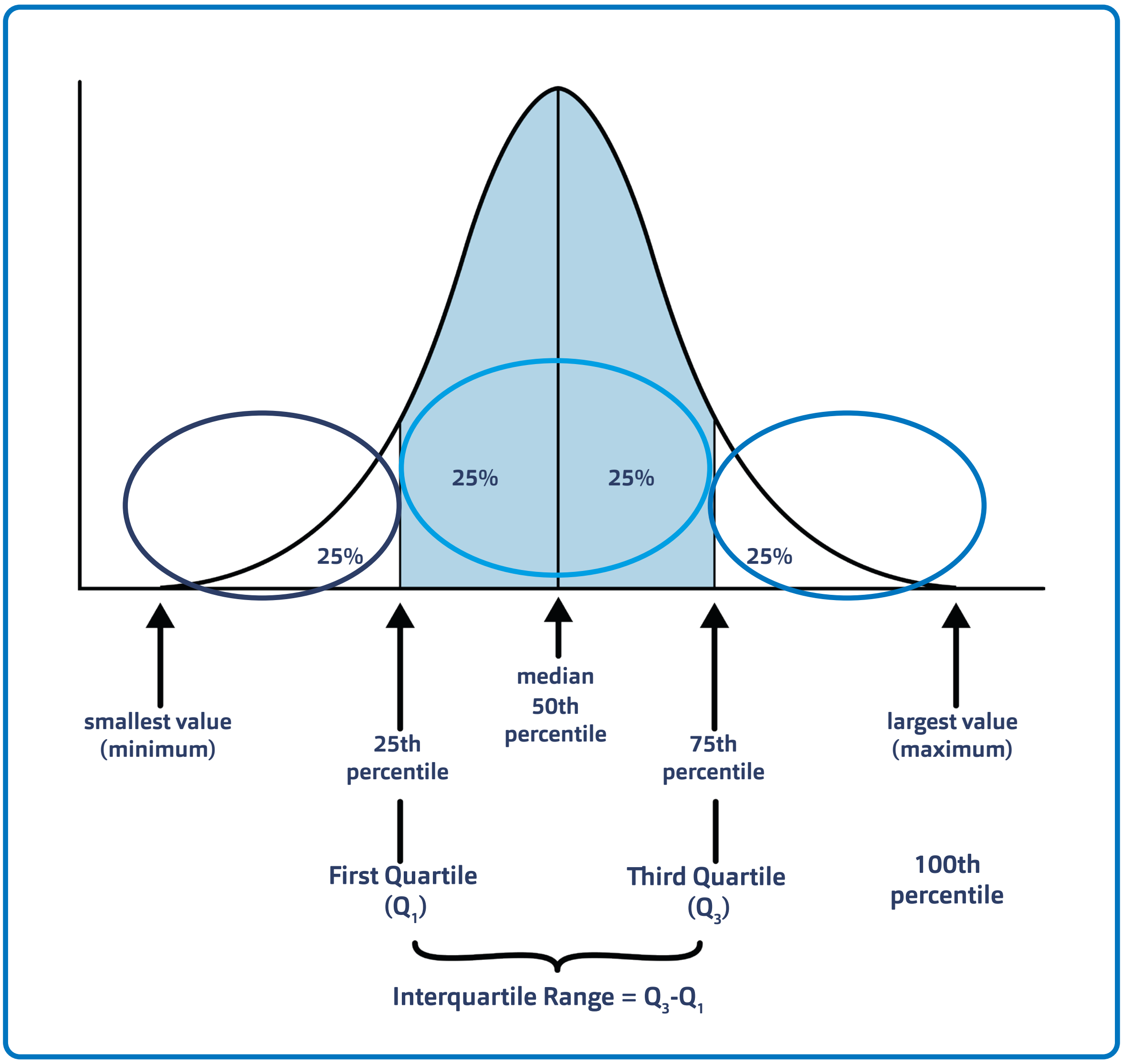


Figure 1. Interquartile ranges, splitting the cohort in lower priority, typical priority and higher priority categories.

Background information immersion

Immersion is the degree of sinking into a cushion. Immersion often goes hand in hand with envelopment, which is the ability of the cushion to shape around the body. Immersion is necessary to ensure that the cushion can support the pelvis hereby distributing the bodyweight over the biggest possible contact area, leading to less pressure per area.

- Immersion is the ability to sink into a support surface.
- Envelopment is the ability of a support surface to wrap around the shape of the body (PRESSURE ULCER PREVENTION Pressure, Shear, Friction and Microclimate in Context, 2010). Cushion envelopment is the ability to conform around a shape.
- Both immersion and envelopment are required for effective pressure distribution.

The more a cushion allows for immersion and envelopment of a patient, the more effectively **pressure** is redistributed, thus reducing risk of potentially harmful peak pressures. However, excessive immersion leading to the patient sinking too deeply into the cushion can result in bony prominences encountering the underlying wheelchair seat mat or subsurface, a phenomenon known as 'bottoming out'. When bottoming out occurs, peak pressure substantially increases as the support surface fails to provide adequate support *(American National Standard for Support Surfaces-Volume 1: Requirements and Test Methods for Full Body Support Surfaces, n.d.)*. To allow for **optimal envelopment**, typically 40-45mm of immersion is recommended for most individuals. To meet the US code for "skin protection" wheelchair cushions must demonstrate at least 40mm of immersion. Additionally, proper immersion is crucial because the ischial tuberosities (ITs) are situated lower than the trochanters and thighs, requiring the pelvis to sink in the cushion adequately to support other parts of the body/ pelvis as well, and redistribute pressure away from the IT's.

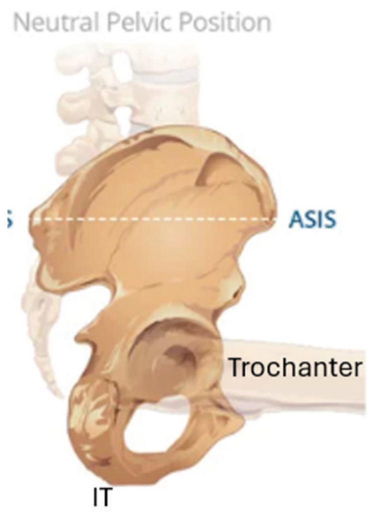


Figure 2. A neutral pelvic position, showing the IT's which are positioned lower compared to the trochanter. The Posterior superior iliac spine (PSIS) and anterior superior iliac spine (ASIS) are horizontally levelled indicating a neutral pelvis.

Critical immersion marks the threshold beyond which further increases in immersion lead to diminished effectiveness in pressure redistribution (European Pressure Ulcer Advisory Panel, National Pressure Injury Advisory Panel, 2019). Peak pressures are at their lowest just before the patient reaches the bottoming-out point. The American National Standards for Support Surfaces (2014) defines bottoming out as "the state of support surface deformation at which no increase in cushion deformation occurs when further loading is applied" (American National Standard for Support Surfaces-Volume 1: Requirements and Test Methods for Full Body Support Surfaces, n.d.) (see figure 4). With foam-based cushions this can occur well before the 'encountering the underlying wheelchair seat mat or surface', since the foam stops deforming before the user encounters the underlying wheelchair seat mat or surface. When foam ages this process happens quicker (Noble et al., 1984). Bottoming out can happen with adjustable cushions and non-adjustable cushions like foam.

The challenge with critical immersion lies in its proximity to the bottoming-out point. This means that any movement or change in position may cause the patient to bottom out. Therefore, it is essential to maintain a 'safety zone' to mitigate the risks of bottoming out as the patient shifts position. The 'safe zone' can be defined as the region where envelopment and immersion are optimized without the risk of bottoming out.

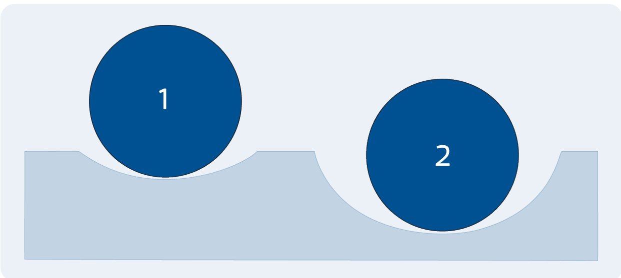


Figure 3. 1: Low immersion, 2: High immersion

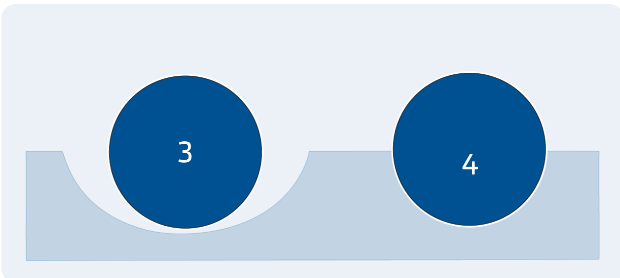


Figure 4. 3: Low envelopment, 2: High envelopment

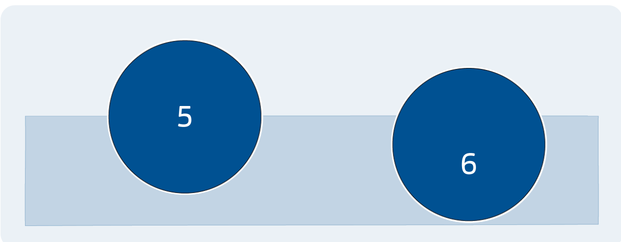


Figure 5 5: Effective immersion & envelopment,
6: High envelopment, but bottoming out (too much immersion).

Different manufacturers have defined different points for critical immersion. The manufacturer of the interconnected air cell cushion defines the safe zone: ½” - 1” (1.5 – 2.5cm) recommended distance between the individual and the seating surface. (ROHO ® DRY FLOATATION ® Wheelchair Cushions Operation Manual, 2019). The Vicair manual states that for users there needs to be at least 2.5cm/1” of SmartCells™ below the lowest bony prominence.

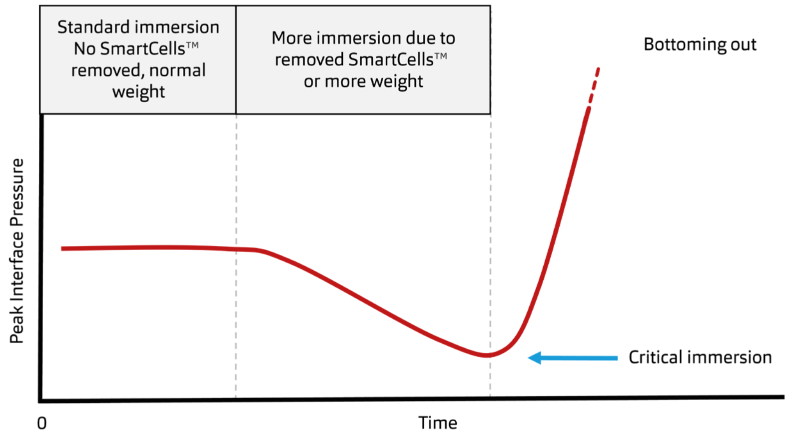


Figure 6 (right). Curve of the peak interface pressure dependent of the degree of immersion

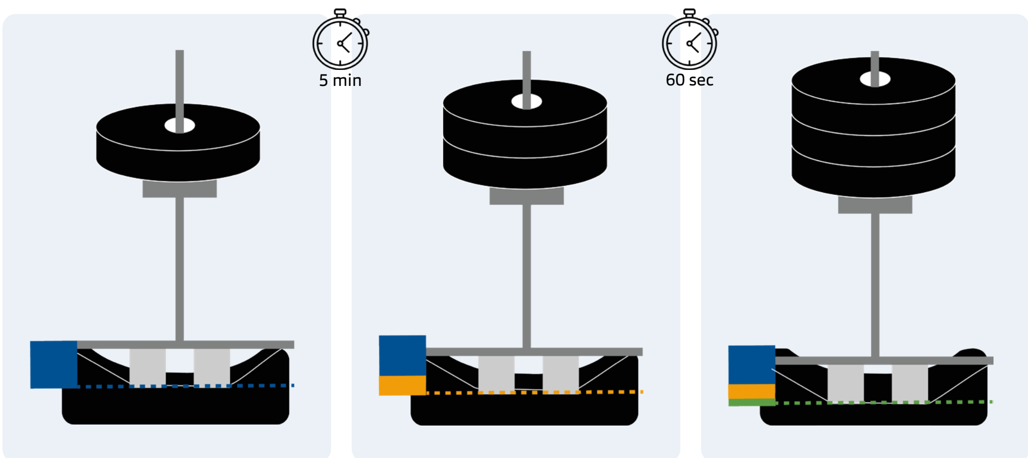
Bottoming out may occur at a bony prominence, such as the ischial tuberosity, greater trochanter and/or sacrum. Luckily bottoming out normally does not take place on a Vicair cushion, neither in case of normal use nor during misuse (de Groot et al., 2022). The immersion for the Vicair Adjuster O2 as well as the Vicair Vector O2 is around the 72% of the measured height, found during independent ISO 16840 lab tests conducted at Pittsburgh University.

In summary, immersion is important to help protect the skin, support the pelvis and redistribute the pressure.

Loaded contour depth & envelopment immersion - Results

Immersion is of such importance that there are multiple tests included to measure it. The first way ISO prescribes is with the **loaded contour depth test**. Two bigger cylinders representing the IT’s and two smaller cylinders representing the greater trochanters (GT’s) are pressed into the cushion. It is a test to assess the ability of a cushion to immerse and envelop the pelvic area/skeleton (the indenter does not include any legs). The test consists of measuring the immersion after 5 minutes and applying a load of 135N, immersion is measured again after 60seconds with a load of 175N, then again after 60seconds with a load of 225N. The test is repeated 3 times, and the average of theses test results is reported.

Metrics & Result ranges*



Loaded contour depth (mm): The depth of immersion of the basepoints (ITs) of a cushion loading indenter.

Observed range: 13-85 mm

Overload deflection 1 (mm): The additional immersion from the nominal load with a 33% increase in load.

Observed range: 1-8 mm

Overload deflection 2 (mm): The additional immersion from the nominal load with a 66% increase in load.

Observed range: 4-14 mm

Loaded countour depth

This test measures the ability of a cushion to maintain tissue integrity by its ability to immerse en envelop the buttocks.

**Result ranges declared herein were measured in testing to date and are not a defined range that results must fall within*

Figure 7. Figure of the loaded contour depth test (ISO-16840-6:2015) (The International Organization for Standardization (ISO), 2015)

Clinical Implications: a higher loaded contour depth indicates more immersion into the cushion and better distribution of pressure on the soft tissue (as long as there is no bottoming out). Cushions with higher additional immersion under the overload conditions have higher margins of safety against bottoming out.

Envelopment immersion

The second way to test it is by the **envelopment immersion test**. The indenters used in this test are more representative of the human buttocks shape (two dual semi spherical indenters one 220mm and the other 255mm, see figure 7). First 425N (43kg) (Nominal load) is applied for 60 seconds followed by 525N (53.5kg) (overload test) for 120 seconds, at both weights the immersion is registered. The average of 3 trials is reported. Guidance to interpretate the results: a higher immersion under the nominal load conditions indicates more immersion into the cushion and distribution of pressure on the soft tissue. Cushions with higher additional immersion under the overload conditions have a higher margin of safety against bottoming out.

The immersion for the loaded contour depth was for the Vicair Adjuster O2 and the Vicair Vector O2 similar and in the highest category. Both cushions are in the top 3 (highest percentile) results of Pittsburgh. The Envelopment - immersion test shows similar results.

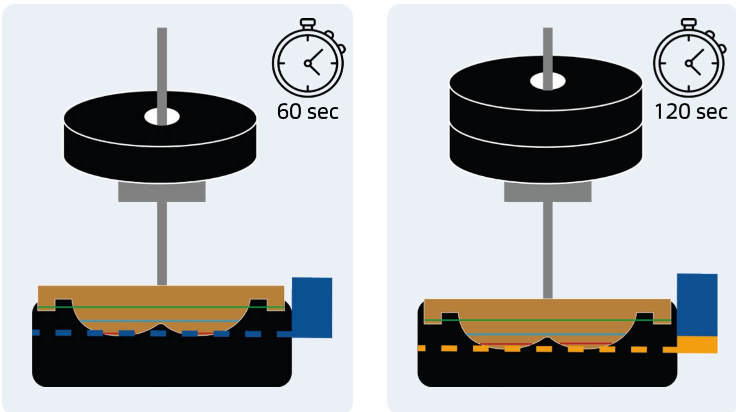
PRESSURE

Envelopment - immersion

Metrics & result ranges*

This test characterizes a wheelchair cushion's ability to envelop and immerse the buttocks. Two sizes of dual semi spherical indenteres and two loads are applied to assess the ability of the cushion to adjust to changes in size and weight.

Immersion**



Nominal load immersion (mm): The depth of immersion of the basepoints (ITs) of the indenter at nominal load.

Observed Range: 26-89 mm

Additional immersion with overload (mm): The depth of additional immersion of the basepoints (ITs) with a 24% increase in load from nominal.

Observed range: 1-5 mm

**Result ranges declared herein were measured in testing to date and are not a defined range that results must fall within*

*** Values for large (255 mm) indenter*

Figure 8. Envelopment – immersion ISO test. The test characterizes a wheelchair cushion's ability to envelop and immerse the buttocks. (ISO-16840-12:2021) (The International Organization for Standardization (ISO), 2021)

Envelopment - offloading

Immersion indicates the depth to which the body sinks into the cushion, without providing insight into how effectively the cushion conforms to the body. The objective is to maximize contact and support between the body and the cushion in order to minimize pressure. Key parameters in this context include 'contact area' and envelopment. Contact area refers to the number of pressure sensors on the measuring system that come into contact with the user, yet the pressure mapping itself may, depending on the model, exhibit some rigidity, hindering an accurate assessment of envelopment. Therefore, the ISO 16840 standard committee devised an additional test to measure user envelopment. This test employs an indenter curved to mimic the shape of the human buttocks, with 18 holes housing small sensors for direct pressure readings. These sensors are positioned at various points along the curved surface, providing a more comprehensive indication of how the load is distributed across the contours. Interpretation of these sensor readings also offers insight into the cushion's offloading capabilities. Because no wheelchair user is the same, this test is performed at 2 different loads (425N & 525N) and 2 different indenter widths. For each set up the test is repeated 3 times, and the average is reported.

Offloading involves redistributing pressure from one area to another to reduce pressure on high-risk areas. Given the varied sensors on the indenter, the percentage of offloading can be determined by using the formula: ((Non-IT pressure/total pressure)*100%).

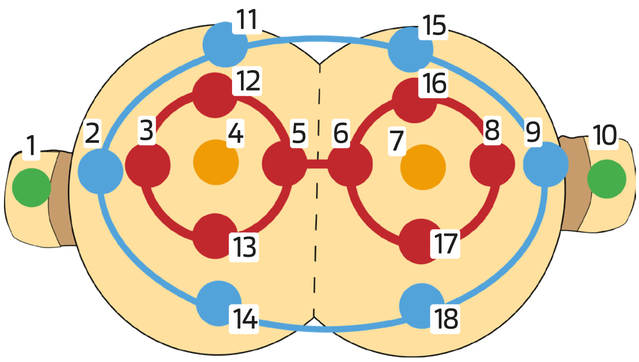
PRESSURE

Envelopment - Pressure

Metrics & result ranges*

This test characterizes a wheelchair cushion's ability to envelop and immerse the buttocks. Two sizes of dual semi spherical indenteres and two loads are applied to assess the ability of the cushion to adjust to changes in size and weight.

Envelopment**



Pressure at 4 elevations (mmHg): Average pressure at each of 4 elevations (E1-E4) of the indenter under standard and overload conditions depth of immersion of the basepoints (ITs) of a cushion loading indenter.

Observed ranges:

E1	44 - 137 mmHg
E2	14 - 236 mmHg
E3	61 - 160 mmHg
E4	00 - 237 mmHg

Guidance

Envelopment: The ability to conform to the contour of the body

The pressure averages at each of the four elevations provide information on the cushion's ability to redistribute forces. Similar pressure values at each elevation indicate good envelopment. Lower pressure at the lowest elevation (E1) representing the ITs is also desirable.

**Result ranges declared herein were measured in testing to date and are not a defined range that results must fall within*
*** Values for large (255 mm) indenter*

Figure 9. Envelopment – pressure. This test characterizes a wheelchair cushion's ability to envelop and immerse the buttocks (ISO-16840-6:2015) (The International Organization for Standardization (ISO), 2015).

Results

Vicair Vector O2 scores in the higher category for offloading at 525N with the large indenter, while Adjuster O2 demonstrated medium offloading at 425N with the small indenter.

Clinical Implications: Envelopment is optimized when the contact area between the support surface and the supported body part increases, resulting in reduced pressure across the weight-bearing surface. Therefore, greater envelopment is desirable. More offloading means less pressure at the high-risk area of the IT's. Not for everyone that is needed or desirable, it is just handy to know when choosing a cushion.

Contact area & Dispersion index

Pressure mapping involves the utilization of a rigid indenter resembling the shape of the human buttocks. Although the ISO indenter does not replicate the exact characteristics of the human body, it provides a standardized shape, size, and stiffness for the application of a standardized weight, which is integral to the comprehensive scientific testing protocol. This ensures that tests can be replicated, and data can be compared effectively, particularly when assessing the impact of altering cushions or covers. During pressure mapping, the cushion is subjected to loading using a rigid cushion loading indenter with a total load of 500N (as depicted in figure 6A), and the pressure mapping device is positioned between the cushion and the indenter. The pressure mapping device records data for a duration of 60 seconds. An average of five trials is calculated and reported.

Contact area is another way to measure envelopment. It is determined using a pressure mapping system. Envelopment is optimized when the contact area between the support surface and the body part is at its maximum, resulting in reduced pressure across the weight-bearing surface. Contact area is specifically defined as the portion of a cushion's pressure map where sensors register values of 5mmHg or higher. The average of this value across five trials is computed.

The dispersion index is calculated by summing the pressure readings in the base point zones (most convex areas of the indenter) and dividing by the sum of all pressure readings, expressed as a percentage. The mean of this value across five trials is determined.

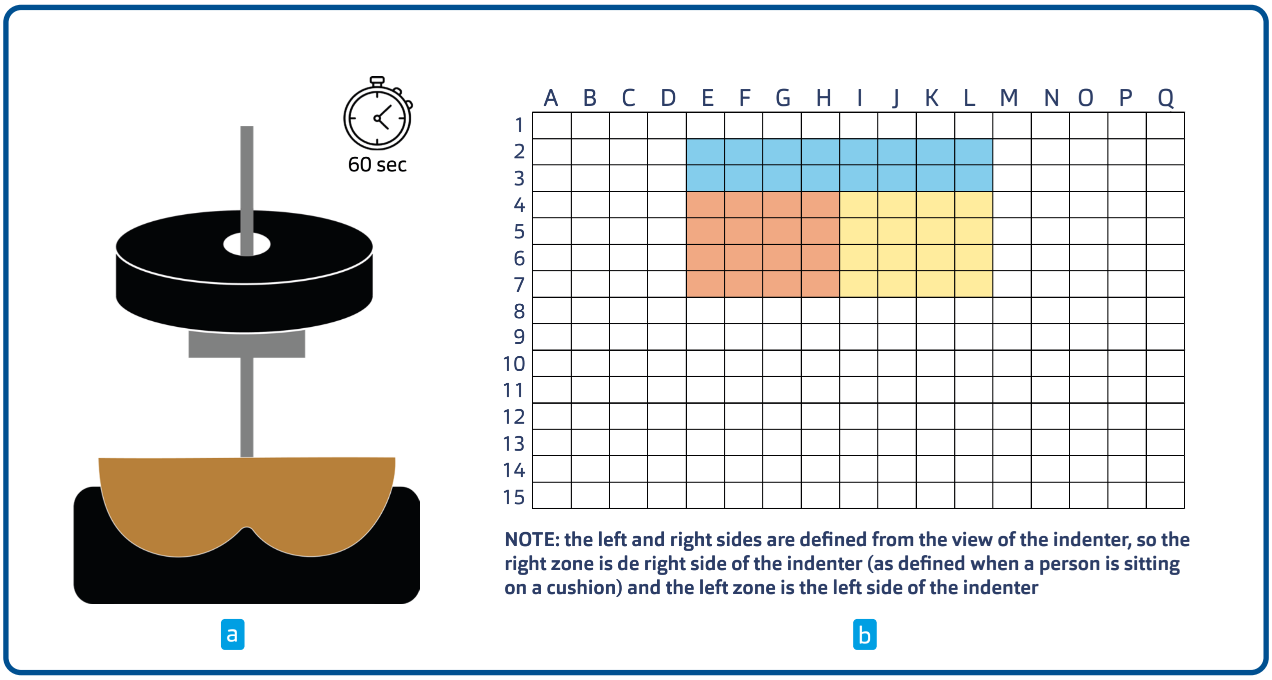


Figure 10a: the cushion loading indenter. 10b: Guidance on interpretation of the pressure map and base zones. Representation of a pressure map that shows the left base zone (yellow), right base zone (Orange) and Center (blue) zone. (Wheelchair and Cushion Standards Group - University of Pittsburgh, 2024).

Clinical Implications: A higher contact area means a bigger support area over which the pressure can be distributed, resulting in a lower pressure per cm2. A lower dispersion index means less pressure in the higher risk area's (IT's, sacrum) and a more effective pressure distribution.

The results in perspective: The contact area for both cushions fell in the top quarter of the Pittsburgh cohort (50 cushions tested). The dispersion index too fell in the top desired range, top 10.

The peak pressure index results fell within the middle of the range of the test cohort.

Discussion – limitation of the standards

ISO standards are designed for testing physical product characteristics under controlled laboratory conditions, but they may not fully represent clinical practice or human anatomy. Thus, cushion performance in real-world settings may vary. The goal of these standards is to measure key product characteristics in a scientific, repeatable manner, facilitating objective comparisons of properties and solutions. However, standards are not intended to endorse specific solutions; rather, they enable direct comparison of critical properties identified by standards committees. Moreover, standards usually lack pass/fail boundaries because individuals have unique risks, challenges, needs and different susceptibilities. Therefore, standards are primarily used to compare performance characteristics desired by clients. A common issue is that one should consider the entirety of all characteristics rather than focusing on one characteristic individually. Some characteristics are difficult to reconcile.

Conclusion – Skin protection

An optimal immersion and envelopment are key characteristics for an optimal pressure distribution, lowering the chance of pressure injury development. The Vicair cushions perform in the highest skin protection categories tested by Pittsburgh according to the ISO Standards. See figure 11 with the pie charts.

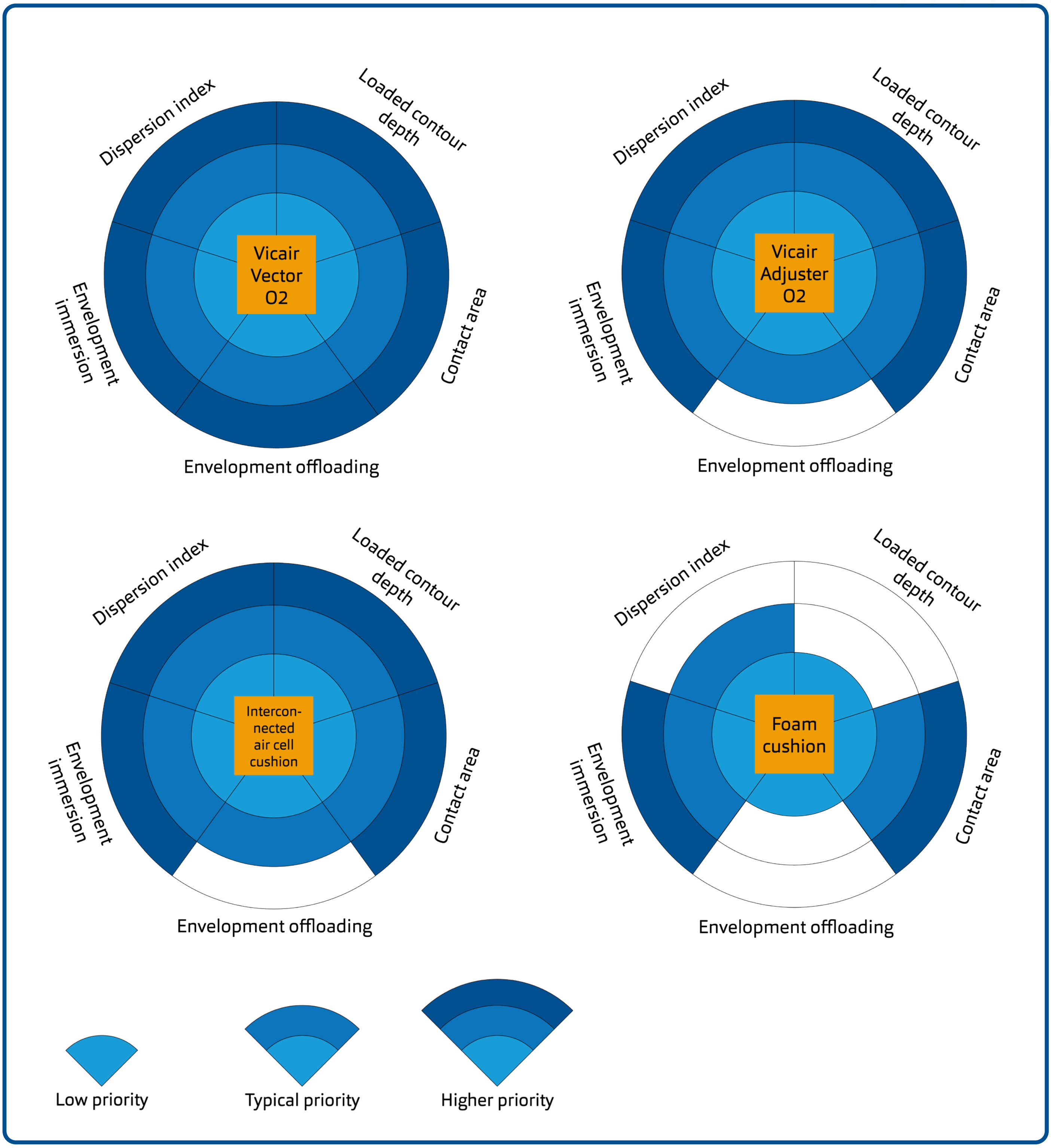


Figure 11. Overview of all the performed tests related to skin protection. The Vicair Adjuster O2, Vicair Vector O2, interconnected air cell cushions and a reference foam cushion are displayed. The number of pie parts coloured refers to the performance category of the test. 1= lower priority, 2= typical priority, 3= higher priority.

Stability

There are several stability tests performed by Pittsburgh University:

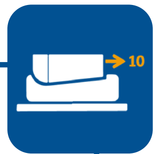
- Horizontal stiffness – ISO 16840-2:2018
- Shear force – ISO 16840-2:2018
- Lateral stability – ISO 16840-13:2021

Horizontal stiffness

The NPIAP/EPUAP/PPIA clinical practice guideline explains how shear forces between the body and a support surface can make tissue deformation worse, leading to pressure injuries. It's not just about the pressure pushing down on the body; when someone sits, there are many different forces at play, like compression, shear, and tension, that can distort the tissues. (See One pager – The importance of skin protection & associated factors, (N. F. L. Conijn et al., 2024)).

To prevent deformation of tissues, the support surface should minimize shear forces as much as possible. While reducing the overall pressure on the body is important, reducing shear forces both at the interface and internally is also crucial in clinical practice. This helps lower the stress and strain on internal tissues.

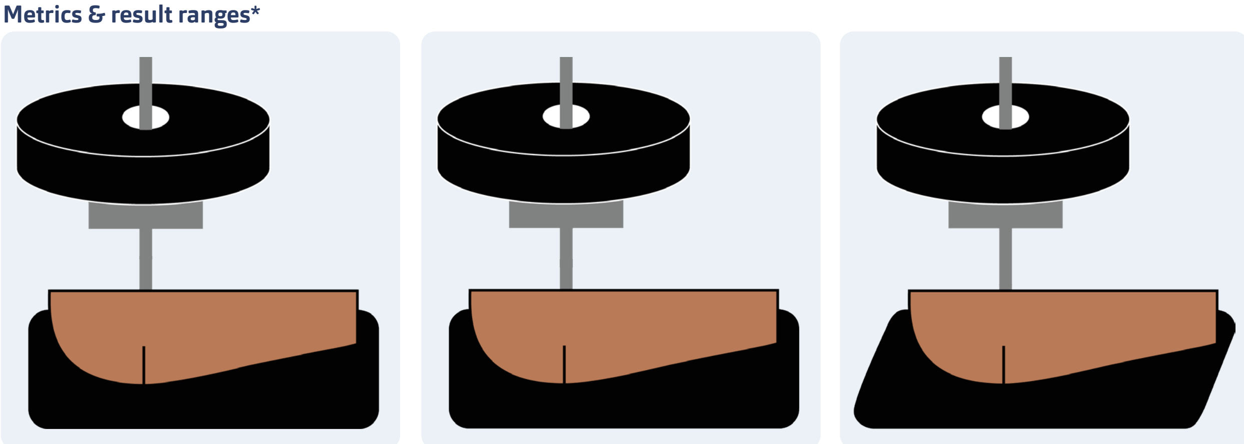
Interface shear force can be measured in the lab with a shear sensor during the horizontal force test and in clinical settings with devices like the iShear, which is a horizonatal shear force measurement device (available through Vicair distribution network) . When we reduce shear forces with cushion or cover designs, we need to make sure we're not compromising other seating goals. For example, a very slippery surface might be good for the tissues but could cause the person to slide forward too easily, affecting their posture and potentially leading to worse pressure distribution. And it's not only about pressure and the prevention of pressure injuries, sitting stable and being able to perform everyday life tasks is just as important. Postural stability refers to the continuous process of postural changes during sitting. The capacity to maintain postural stability in sitting position is a prerequisite to perform activities of daily living (ADLs), reduce risk of shoulder injury and reduce risk of falling. But postural stability is also important for social functioning, satisfaction with equipment, and thus quality of life. Deficits in postural stability can severely limit performance in these aspects of life (Dean et al., 1999; Dyson-Hudson & Kirshblum, 2004; Riley et al., 1995; Trefler et al., 2004). Furthermore, the role of trunk control on shoulder injuries may be an important consideration in mitigating injury and improvement of wheelchair propulsion (Conijn et al., 2023). Wheelchair cushions play an important role in stability, which is demonstrated by Vreede (Vreede, 2018a, 2018b) and in the literature review called postural stability and the effects of wheelchair cushions (N. Conijn, Helming, de Groot, et al., 2023). It is not only the wheelchair cushion, but the wheelchair set-up can also play their part, which is apparent in the case study: Effects of seating posture and wheelchair configuration on pressure distribution and shear forces (Effects of Seating Posture and Wheelchair Configuration on Pressure Distribution and Shear Forces - Case study, 2024) & Effect of wheelchair configuration on posture (N. F. L. Conijn & Helming, 2024).



Horizontal stiffness & shear

This test characterizes the cushion's response to slight horizontal movements in the forward direction, indicating stability and risk to soft tissue due to shear.

Metrics & result ranges*



Peak force (N):
The maximum horizontal force required to displace a cushion loading indenter 10 mm.

Observed Range: 63-369 N

Force at 60 sec (N):
The final force achieved during the 60 sec setting time after movement.

Observed range: 1-5 mm

**Result ranges declared herein were measured in testing to date and are not a defined range that results must fall within*

Figure 12. Horizontal Stiffness test. The test characterizes the cushion's response to slight horizontal movement (1cm) in the forward direction, indicating stability and risk to soft tissue due to shear. Based on the ISO 16840-2:2018 test (The International Organization for Standardization (ISO), 2018).

To test the slipperiness/horizontal stability of wheelchair cushions in a laboratory setting, we use a horizontal force/ stiffness test. We place a rigid indenter, shaped like the buttocks, on the cushion and apply a load of 500N to mimic downward force. Then, we pull the indenter forward with a cable and measure the force needed to drag it across the surface over a set distance (10 mm) . More force needed may mean the person will stay securely in their posture, while less force may indicate a risk of sliding forward.

The ISO protocol also prescribes to use a shear sensor under the simulated IT (ischial tuberosity) to measure localized shear force in an area prone to pressure injuries. High shear forces mean more tissue distortion and higher risk of injury, while low shear forces mean less distortion and potentially lower risk of injury. The Vicair SmartCells™ help distribute shear from the skin to the cushion by deforming and moving slightly.

The ideal cushion has low shear force and high horizontal stiffness, providing resistance against sliding without distorting the tissues. The Vicair Adjuster has the lowest shear force with an average of 6.7N after 3 trials. The Vicair Vector O2 has a slightly higher shear force with 9.8N. Which are both still low forces especially when considering the fact that there is a force pulling the indenter forward with 2mm/s, this force is the horizontal force.

The peak horizontal force for most cushions is the force at the moment of displacement of the indenter. For the Adjuster this was in the middle quarter and for the Vicair Vector O2 in the top quarter. After the initial displacement the resistance force against displacement becomes less, resulting in a final force of the horizontal stiffness test that is lower for all cushions, the Vicair Vector O2 scores in the highest quarter and the Vicair Adjuster O2 in the lowest. The peak force of the Vicair Vector O2 is in the highest quartile of the tested cushions and the Vicair Adjuster O2 in the middle category (see figure 14).

Clinical Implications: A higher Peak or Final Force, or a higher horizontal stiffness, may offer more stability but also an increased chance of tissue deformation due to shear forces between seat cushion and buttocks. Therefor it is important to look at both results in conjunction. The desired combination is a high horizontal force with a low shear force. This indicates a stable cushion with a low risk for skin damage.

The results in perspective: The Vicair Vector O2 falls in the highest quartile of the tested cushions, the Vicair Adjuster O2 in the middle range with respect to the horizontal force, they both have a low shear force. The difference in outcome can be explained by the difference in cushion design. The Vicair Vectors' O2 compartment layout is ideal for stability. On the other hand, the Vicair Adjuster O2 allows for more variation of pelvic obliquity due to more immersion in the bigger rear compartments, making the cushion more adjustable to the user, but the Adjuster therefore has less resistance to movement when it comes to horizontal stiffness. This became also apparent in our research "Pelvic obliquity", which investigates the pelvic obliquity range the Vicair Adjuster O2 can accommodate without adjusting the filling grade (N. Conijn, Helming, & Van Der Heyden, 2023; N. Conijn & Helming, 2023).

Another aspect that is of importance to sit stable on a wheelchair cushion and enables you to perform activities of daily living is the lateral stability.

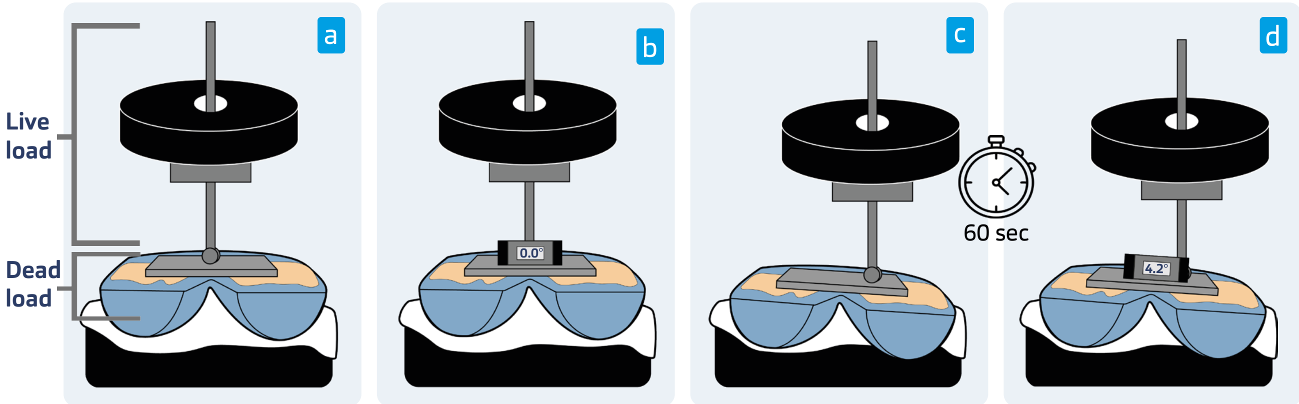
Lateral stability

Like the horizontal stiffness test, the lateral stability test also uses an indenter that mimics a seated body. This test simulates a person leaning or reaching to the side. To do this, a dead load of 200N is applied to the indenter, along with a live load of 300N, which is then shifted sideways. The degree of tilt the indenter experiences in response to this shift is measured during 60s, indicating how stable the cushion might be when someone leans or reaches to the side. This helps us understand if the cushion will keep the person stable or if it might move too much, posing a risk for instability. Results are displayed for 10seconds, representing initial displacement and 60 seconds, representing adjustability of the cushion. The tests are repeated 5 times, and the average is reported. By using this mechanical, scientific approach, we can compare different cushion technologies to see how they might perform compared to others.

The NPIAP/EPUAP/PPPIP clinical practice guidelines offer many factors to consider when selecting support surfaces. A wheelchair cushion must be suitable for the individual, reduce pressure and shear, and offer adequate support. Ensuring a stable support surface is crucial for allowing the individual to carry out their full range of movements and activities.

Defenition of metrics

This test characterizes the cushion's ability to stabilize a user when leaning to the side.



Average tilt angle (°):
The change in orientation of the indenter after a lateral shift in the center of mass, measured at 10 seconds increments for 60 seconds following the shift.

Observed range:
Average tilt angle at 10 seconds: 2.4°-6.9°
Average tilt angle at 60 seconds: 2.7°-7.5°

Figure 13. Lateral stability test, this test characterizes the cushion's ability to stabilize a user when leaning to the side. Test is based on ISO 16840-13:2021 (the International Organization for Standardization (ISO), 2021)

Clinical Implications: A cushion with a lower Average Tilt Angle would offer enhanced support for individuals during lateral leaning. Conversely, a higher Average Tilt Angle suggests that greater effort may be required to return to a neutral position.

The results in perspective: The observed results exhibit substantial variability, ranging from 2.3° of tilt for the most stable cushion to approximately 7.5° for the least stable. Foam cushions demonstrated an average tilt of 6.6° after 60 seconds, while an Interconnected Air-cell cushion falls in the middle category of typical tilt. Various cushions exhibited a wide spectrum of tilt and stability, indicating that outcomes cannot be inferred solely based on material or technology. A cushion that has the main focus on pressure distribution is often not very stable, because stability and 'softness' (needed for pressure distribution) are contradictory of each other. Unless you develop a cushion that consists of hundreds of Vicair SmartCells™ that can individually deform, move and generate stability. Notably, the Vicair Vector O2 and Vicair Adjuster O2 cushions demonstrated superior performance compared to the entire tested cohort, both at 10 seconds and 60 seconds of tilt. Both cushions score very well due to the Vicair technology. The difference in outcome between de Vicair Vector O2 and Vicair Adjuster O2 can be explained by the differences in cushion design, the Vicair Vector O2 is a more stable cushion.

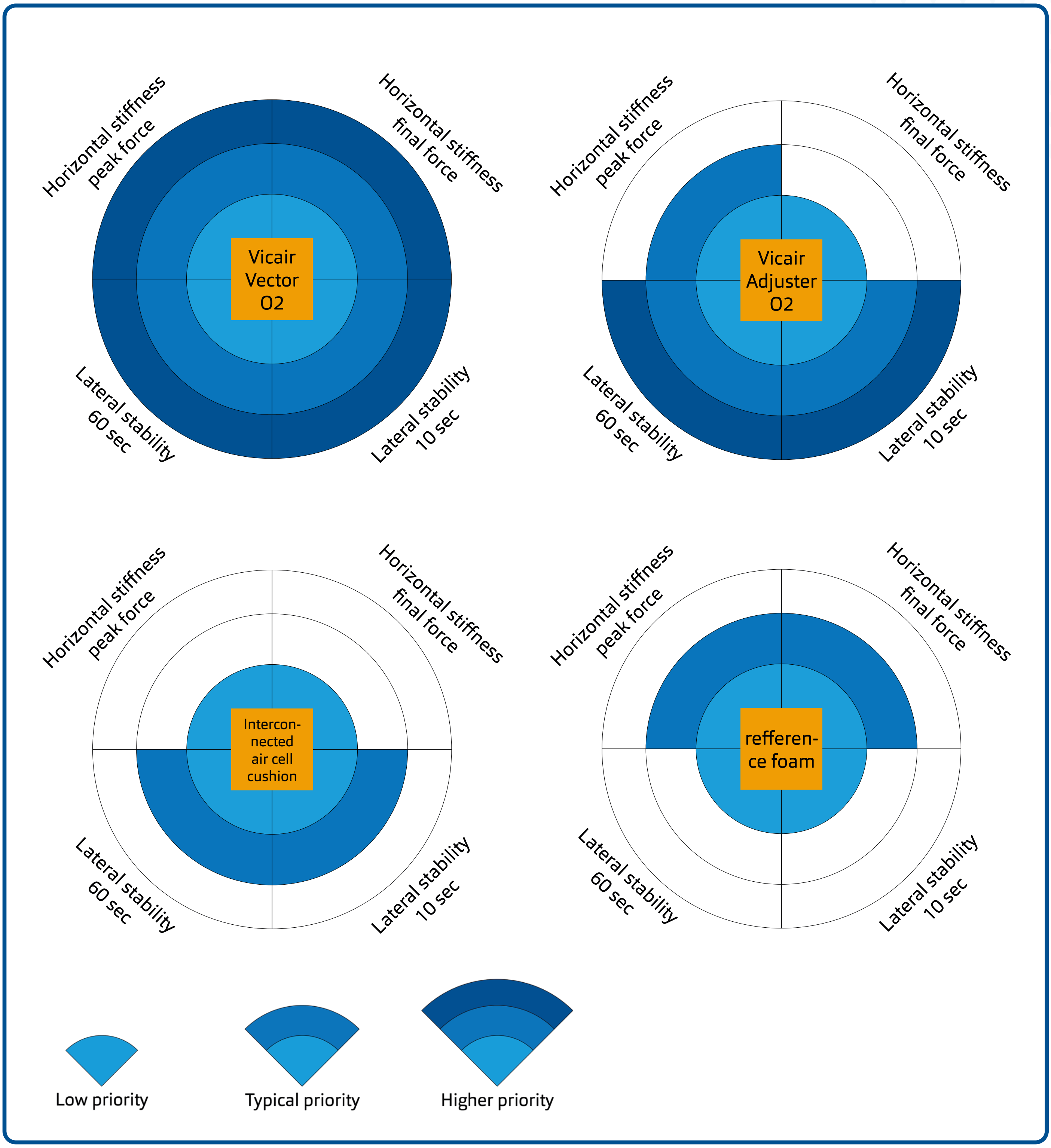


Figure 14. Overview of the stability tests for 4 different cushions. The Vicair Adjuster O2, Vicair Vector O2, interconnected air cell cushions and a reference foam cushion are displayed. The number of pie parts coloured refers to the performance category of the test. 1= lower priority, 2= typical priority, 3= higher priority.

The results in perspective to each other

It is recommended to look at all the tests combined, a cushion is a result of all the tests, not just one. Therefore, a table is created with all the results categorized in 'Higher priority', 'Typical priority' and 'Lower priority'. Here it becomes apparent that cushions that solely use air as their technology to distribute pressure, are not very stable. These cushions perform well in terms of skin protection but lack stability. Vicair SmartCells™ have the ability to distribute air and act like a stable surface, combined with the unique shape of the Vicair Vector O2 this cushion outperforms all the others.

		Test	Vicair Vector O2	Vicair Adjuster O2	Interconnected aircell	Foam	Priority category
Primary performance indicators	Skin protection	Loaded contour depth (immersion)	H	H	H	L	<40mm low 40-45 typical 45-85mm high
Primary performance indicators	Skin protection	Contact area	H	H	H	H	>71276mm^2 high
Primary performance indicators	Skin protection	Envelopment - off-loading	H	M	M	L	<84 low 84-88 typical >88% high *Cushions are categorized in the highest off-loading category from the 4 test*
Primary performance indicators	Stability	Horizontal stiffness - peak force	H	M	L	M	63-126N low 126-161N typical >161N high
Primary performance indicators	Stability	Lateral stability 60 sec	H	H	M	L	6.9°-5.9° low 5.9°-4.2° typical <4.2° high

Table 1. Overview of the primary performance indicators for skin and stability. The primary performance indicators are considered more valuable indicators compared to the secondary performance indicators, due to the nature of the tests and what is important for a client. Legenda: Green=higher priority, yellow=typical priority, red=lower priority

		Test	Vicair Vector O2	Vicair Adjuster O2	Interconnected aircell	Foam	Priority category
Secondary performance indicators	Skin protection	Dispersion index	H	H	H	M	63-49% typical 49-24% high
Secondary performance indicators	Skin protection	Envelopment immersion small indenter	H	H	H	H	45-89mm high
Secondary performance indicators	Skin protection	Envelopment immersion large indenter	H	H	H	H	45-89mm high
Secondary performance indicators	Stability	Horizontal stiffness - final force	H	L	L	M	42-82N low 82-118N typical 118-254N high
Secondary performance indicators	Stability	Lateral stability 10 sec	H	H	M	L	6.9°-5.5° low 5.5°-3.7° typical <3.7° high
Secondary performance indicators	Others	Impact dampening ratio	M	M	M	H	46-31% typical <31% high
Secondary performance indicators	Others	Impact dampening initial	H	M	M	H	32.4-23.6 typical <23.6m/s^2 high
Secondary performance indicators	Others	Hysteresis 250N	M	L	L	M	48-16% low 16-9% typical <9% high
Secondary performance indicators	Others	Hysteresis 500N	M	M	L	L	27-12% low 12-5% typical <5% high
Secondary performance indicators	Others	10% force deflection	H	H	M	L	383N-104N low 104N-22N typical <22N high

Table 2. Secondary performance indicators for skin, stability and the other performance indicators.

The following performance indicators are considered others performance indicators:

- Impact damping initial & ration (ISO 16840-2:2018)
- Hysteresis 250 & 500N (ISO 16840-2:2018)
- 10% force deflection (ISO 16840-6:2015)

Other performance indicators

The other performance indicators are seen as less valuable to distinguish cushions or because other factors also play a role. For instance, impact damping is also highly influenced by the wheelchair(Misch et al., 2022), therefor considering the impact damping of the cushion very important is not realistic. Especially hysteresis should be seen in combination with other tests, only a good hysteresis will not tell you whether the cushion is a good wheelchair cushion, whether the cushion distributes pressure, etc. And hysteresis and 10% force deflection are both tests that characterize the medium itself.

Impact damping and hysteresis tests are both used to evaluate the dynamic performance of wheelchair cushions. The impact damping test assesses a cushion's capacity to dissipate energy, which reduces the loading impact on body tissues and supports postural stability (Kalliat et al., 2019). In real-life scenarios, such as when a wheelchair encounters obstacles or rolls off a curb, this characteristic is crucial. Tissues become more vulnerable to pressure injuries under higher loads or repeated impacts, making effective impact damping essential.

Conversely, the hysteresis test measures how much energy the cushion absorbs during each cycle of compression and release. For example, when descending steps or navigating rough terrain, a cushion with higher hysteresis absorbs more energy and transfers less to the user's tissues, providing better shock absorption (ANSI/RESNA, 2018).

The test called Impact dampening is defined in ISO 16840-2:2018, clause 9. This test measures how well a cushion reduces the force of sudden impact, such as going of a curb, this impact can have effect on tissue viability and postural stability. There are 2 main outcomes of the test:

- Impact 1 (m/s2): the force when you first hit the cushion, or in more scientific terms the magnitude of the acceleration at the initial impact of a cushion loading indenter.
- Impact 2/impact 1 Ratio (%): shows how much energy is absorbed after the first hit. It is a ratio of the second to the initial impact as a percentage.

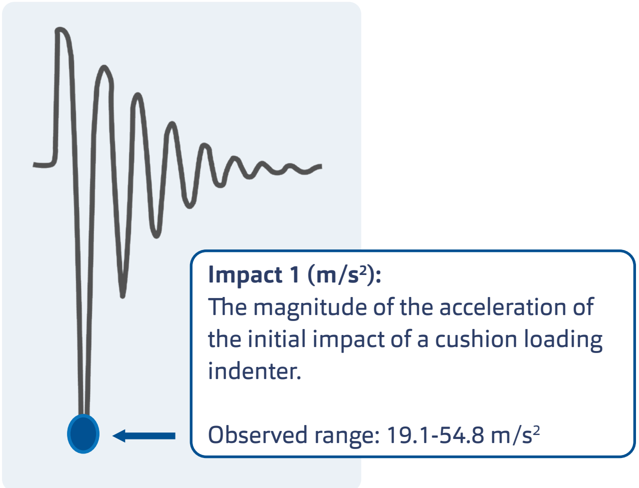
The other outcome is a plot of smoothed acceleration against time in seconds. The test is executed with a test load of 500N, the cushion with indenter is placed at an angle with a stud, this stud is pulled away, creating the impact. The test takes as long as it takes the indenter to settle after impact. The averages of 3 repetitions are reported.

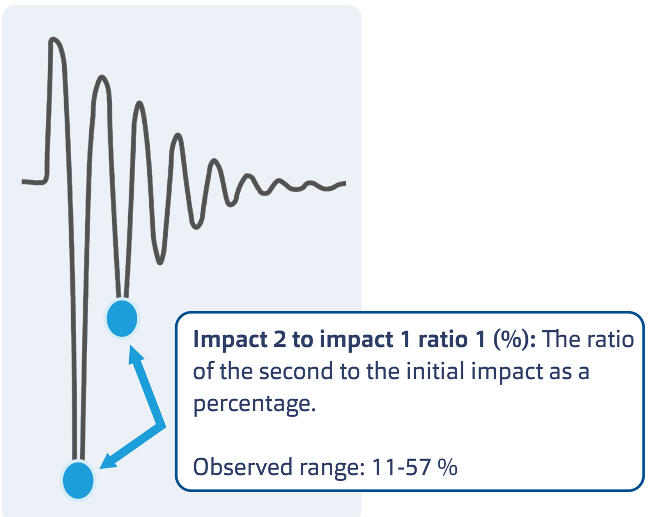
Clinical implications: a lower impact 1 indicates better comfort and postural stability. A lower impact2/impact 1 ratio indicates better absorption of energy after initial contact, decreasing tissue loads and reducing bouncing. Higher impact 1 is a harder cushion on impact.

Impact damping

This test indicates the ability of a wheelchair cushion to reduce impact loading on tissues and help to maintain postural stability when performing tasks such as going off a curb.

Metrics & result ranges*





**Result ranges declared herein were measured in testing to date and are not a defined range that results must fall within*

Figure 15. Impact damping. The test indicates the ability of a wheelchair cushion to reduce impact loading on tissues and help to maintain postural stability when performing tasks. The figure shows the graph that is made during the test.

In case you as a wheelchair users are performing total off-loading by putting pressure on your arms and lift off the cushion and you suddenly lose strength. Falling back onto a cushion with poor impact damping could cause skin damage. It is the crumple zone of your wheelchair cushion to prevent skin damage. A good cushion reduces this risk, protecting your skin and keeping you comfortable.

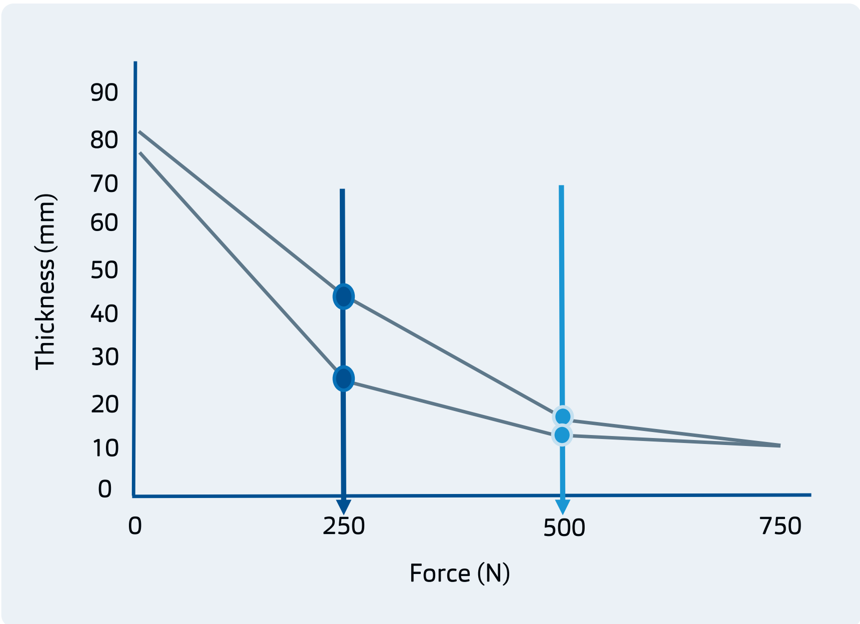
The results in perspective: The Vicair Vector O2 is a more stable basis for the user and therefore better equipped to dampen the initial impact. The Vicair Adjuster allows for the indenter to sink in after impact and is therefore less effective in dampening the impact. The Vicair Adjuster O2 falls in the typical category for both initial and ratio. The Vicair Vector O2 falls in the highest category for the initial dampening and in the typical category for the ratio. Due to the elasticity of foam, foam falls in the higher priority category for impact damping. The interconnected air-cell cushion falls in the same category (typical) as the Vicair Adjuster O2 for both the outcomes.

While this test indicates the way the cushion material responds to impact, the entire wheelchair system contributes to transferring or damping impact (wheelchair frame, casters, forks, etc). For this reason, it was considered a secondary performance metric.

Hysteresis

This test characterizes the cushion's ability to consistently provide support during a cycle of loeading and unloading.

Metrics & result ranges*



250N Hysteresis (%): The difference between cushion thickness at 250 N during loading and unloading expressed as a percentage of loaded thickness.

Observed range: 3-48 %

250N Hysteresis (%): The difference between cushion thickness at 250 N during loading and unloading expressed as a percentage of loaded thickness.

Observed range: 3-48 %

Figure 16. Hysteresis indicates a cushion's ability to consistently provide support during a cycle of loading and unloading. The graph shown is the initial thickness during loading (top line) and the thickness (bottom line) during unloading.

Hysteresis of a wheelchair cushion is described in ISO 16840-2:2018, clause 14. This hysteresis test indicates a cushion's ability to consistently provide support during a cycle of loading and unloading. The initial thickness of the cushion is determined under 8N load (light pressure). The deflection, cushion thickness, is measured from that point. The differences in cushion thickness between loading and unloading is the hysteresis (%). The test load increases from 0-250-500-750N and back to 500 – 250 – 0 N. The results are shown for 250 and 500N and the average of 3 trials is reported.

Hysteresis is a measure of the energy lost to the cushion during a cycle of loading and unloading and with that also the ability for a cushion to maintain its supportive force after being loaded. A lower hysteresis means the cushion loses less energy and maintains better support. When looking from another perspective: if the cushion retains more energy within the cushion material (higher hysteresis value) it will also transmit less energy back to the user, which is beneficial when traversing uneven surfaces or descending stairs.

Clinical implications: a lower ratio means there is less energy lost to the cushion, which is assumed to be better. The larger the hysteresis the lower the ability of the cushion to maintain support during loading and unloading, or the greater the tendency to conform to the user and maintain the contoured shape. A cushion that exactly conforms to the user and maintain the contour shape has a ratio of 0 because the thickness is no different between loading and unloading.

Clinically it is fitting/accommodating and following of the user's buttock by the cushion with added/decreased pressure. Foam cushions have a decreased hysteresis over time, the ratio between loaded and unloaded decreases because foam loses their elastic characteristics (Manko et al., 2019). And with that the support a foam cushion gives over time is decreasing. It is important to look at all the tests as a whole, and in this case also at the differences in values for 250 and 500N. A brick will have perfect hysteresis because the cushion thickness will be the same during loading and unloading for both 500 and 250N, but this is not what you want. A brick will not maintain the contoured shape, but it will also not contour in the first place and with that will not distribute the pressure evenly over the whole surface. When looking at this analogy higher hysteresis improves shock absorption, reducing strain on the user's tissues and enhancing comfort.

The results in perspective: We can debate about what values are desirable, the values are categorised, low values are a higher priority category, high values are a low priority category. The moment you're sitting on a Vicair cushion the cushions adjusts to your body, the Vicair SmartCells™ move and give your buttock the space that is needed. But if you're getting off the cushion, you still see some of the shape of the user, so the cushion does not come back completely. This is because the SmartCells have found a new place to sit and shape around the user's contact area, the air that was between the SmartCells has become less and since this is not packed air (unlike the SmartCells), the air can freely move away. Only by shaking up the cushion it will get back to the original thickness and the shape will disappear, showing a balance between adapting to the user and returning to form. This is why Vicair cushion for 500N perform in the typical category, for 250N the Vector falls also in the typical category but the Vicair Adjuster O2 just falls in the low priority category. The interconnected air-cell cushion falls for both tests in the low priority category, unless the foam cushion which falls in the typical category for 250N and in the low category for 500N. Indicating that the foam cushion is not elastic enough to have a perfect hysteresis.

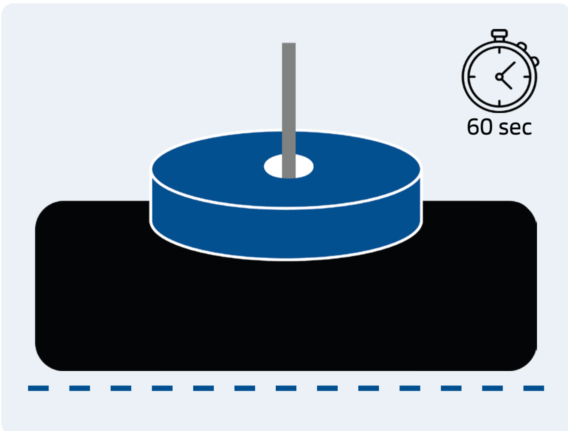
The 10% force deflection is defined in ISO 16840-6:2015 clause 20, it is a test to evaluate a cushion's ability to "cushion" or elastically deform by measuring the force necessary to produce a deflection of 10% of the cushion thickness. In other words, it measures a cushion's initial softness and comfort. This metric helps to characterize how soft or firm a cushion feels when a user initially sits down (first 10% compression).

During the test the cushion is compressed for 10% of the total thickness during 60 seconds, the outcome is the average force that it costed to compress the cushion. The test is repeated 3x and that average is reported.

10% Force deflection

This test characterizes the cushion's surface properties.

Definition of metrics



Compress cushion 10% of the total thickness for 60 seconds and record Average Force.

Average force (N): The force needed to compress the cushion 10% after 60 seconds.

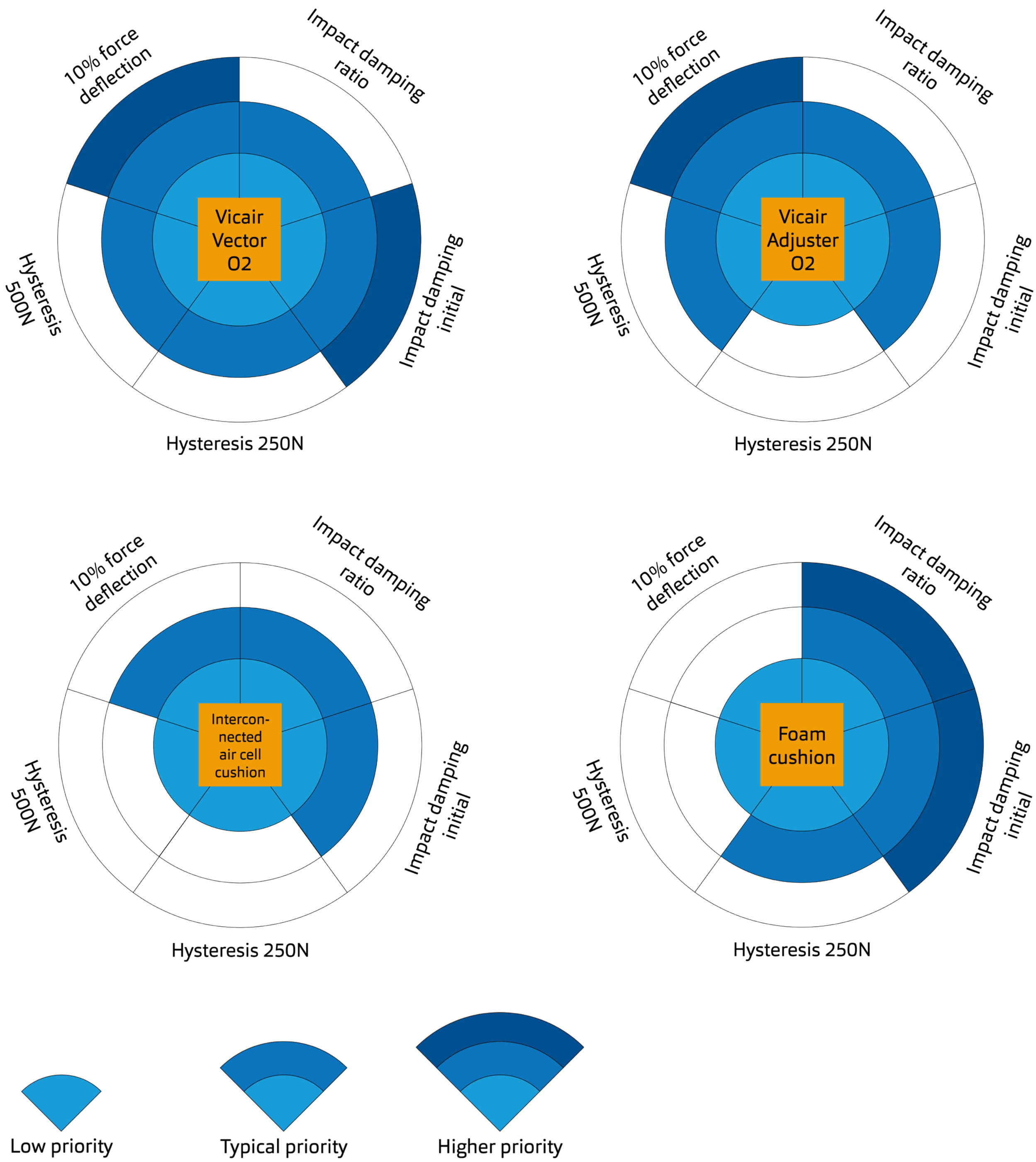
Figure 17. The 10% force deflection is a metric that characterizes the cushion's surface properties

Clinical implications: a cushion that requires a lower average force to produce a 10% compression of its total thickness has a less stiff, more compliant cushion surface. A higher average force may indicate a harder, stiffer cushion surface. A low 10% force deflection indicates a low surface tension, so easy immersion into the cushion. It describes how easy you will come to immersing in the cushion. A cushion with a low 10% force deflection value indicates a softer cushion, which may be more comfortable initially but can also affect stability negatively. Lower 10% force deflection values should be paired with a good design to maintain stability. This test allows clinicians and users to balance comfort with support based on the user's need and preferences.

Both hysteresis and 10% force deflection characterize the cushion medium itself.

The results in perspective: the force deflections for the Vicair cushions are among the lowest of the tested cohort, de Vicair Vector O2 performs better than the Vicair Adjuster O2, but both are in the highest priority category. As discussed above this could influence the cushion's stability negatively. Luckily that is not the case for the Vicair cushions since they use the SmartCells in different compartments, making the cushion really stable but also having a low 10% force deflection.

There is a wide range within the cohort from 9N for the most compliant cushion to 383N for the hardest/stiffest cushion. The interconnected air-cell cushion performs in the typical priority category, while the reference foam is placed in the lower priority for force deflection.



References

American National Standard for Support Surfaces-Volume 1: Requirements and Test Methods for Full Body Support Surfaces. (n.d.).

ANSI/RESNA. (2018). *RESNA American National Standard for Wheelchairs - Volume 3: Wheelchair Seating.*

Conijn, N. F. L., & Helming, T. (2024). *Effects of Wheelchair Configuration on Posture.*

Conijn, N. F. L., Van Der Heyden, B., & Helming, T. (2024). *The importance of skin protection & associated factors.*

Conijn, N., & Helming, T. (2023). *Pelvic Obliquity - Research one pager* (Vol. 6, Issue 3). Elsevier Inc.

Conijn, N., Helming, T., de Groot, L., & Van Der Heyden, B. (2023). *Postural Stability and the Effects of Wheelchair Cushions - Literature Review.*

Conijn, N., Helming, T., & Van Der Heyden, B. (2023). *Pelvic Obliquity in the Wheelchair Using Population - Literature Review.* Elsevier Inc.

de Groot, L., Helming, T., & Kramer, C. (2022). *The effects of misuse of your wheelchair cushion 04.3REV8.22.*

Dean, C. M., Shephert, R. B., & Adams, R. D. (1999). Sitting balance II: reach direction and thigh support affect the contribution of the lower limbs when reaching beyond arm's length in sitting. *Elsevier - Gaid and Posture, 10,* 147–153.

Dyson-Hudson, T. A., & Kirshblum, S. C. (2004). Shoulder pain in chronic spinal cord injury, Part I: Epidemiology, etiology, and pathomechanics. *The Journal of Spinal Cord Medicine, 27*(1), 4–17. https://doi.org/10.1080/10790268.2004.11753724

Effects of Seating Posture and Wheelchair Configuration on Pressure Distribution and Shear Forces - Case Study (March 21, 2024).

European Pressure Ulcer Advisory Panel, National Pressure Injury Advisory Panel, and P. P. P. I. A. (2019). *Prevention and treatment of pressure ulcers/injuries: the international guideline.* file:///C:/Users/15127/Downloads/ggg-quick-reference-guide-version04dec2019-secured (1).pdf

European Pressure Ulcer Advisory Panel, National Pressure Injury Advisory Panel, & Pan Pacific Pressure Injury Alliance. (2019). *Prevention and Treatment of Pressure Ulcers/Injuries: Clinical Practice Guideline. The International Guideline.*

Kalliat, K., Karg, P., Brienza, D., Guzman, S., Freedman, J., & Delazio, A. (2019). *Relationship between impact damping and hysteresis wheelchair cushion performance test results.*

Manko, A., Karg, P., Brienza, D., Delazio, A., Freedman, J., & Williams, E. (2019, June). *Effects of simulated aging on cushion performance metrics.*

Misch, J. P., Liu, Y., & Sprigle, S. (2022). Effect of Wheels, Casters and Forks on Vibration Attenuation and Propulsion Cost of Manual Wheelchairs. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 30, 2661–2670. https://doi.org/10.1109/TNSRE.2022.3205507*

Noble, P. C., Goode, B., Krouskop, T. A., & Crisp, B. (1984). The Influence of Environmental Aging upon the Loadbearing Properties of Polyurethane Foams. *Journal of Rehabilitation Research and Development, 21*(2), 31–38.

PRESSURE ULCER PREVENTION pressure, shear, friction and microclimate in context. (2010). www.epuap.org

Riley, P. O., Benda, B. J., Gill-Body, K. M., & Krebs, D. E. (1995). Phase plane analysis of stability in quiet standing. *Department of Veterans Affairs Journal of Rehabilitation Research and Development, 32*(3), 227–235.

ROHO ® DRY FLOATATION ® Wheelchair Cushions Operation Manual. (2019).

The International Orgainzation for Stadardization (ISO). (2018). *ISO16840-2:2018 Determination of physical and mechanical characterisitcs of seat cushions intended to manage tissue integrity.*

the International Organisation for Standardization (ISO). (2015). *ISO 16840-9:2015 Clinical interface pressure mapping guidelines for seating.* www.iso.org

The International Organization for Standardization (ISO). (2015). *ISO16840-6:2015 Wheelchair seating - Part 6: Simulated use and determination of the changes in properties of seat cushions.*

The International Organization for Standardization (ISO). (2021). *ISO 16840-12:2021 Wheelchair seating-Part 12: Envelopment and immersion characterization of seat cushions using a dual semispherical indenter. www.iso.org*

the International Organization for Standardization (ISO). (2021). *ISO 16840-13:2021 Wheelchair seating-Part 13: Determination of the lateral stability property of a seat cushion.*

Trefler, E., Fitzgerald, S. G., Hobson, D. A., Fitzgerald, S. G., Bursick, T., & Joseph, R. (2004). Outcomes of Wheelchair Systems Intervention With Residents of Long-Term Care Facilities. *Assistive Technology, 16*(1), 18–27. https://doi.org/10.1080/10400435.2004.10132071

Vreede, N. (2018a). *REACH OUT FOR STABILITY* [The Hague University of applied sciences]. https://hbo-kennisbank.nl/details/sharekit_hh:oai:surfsharekit.nl:4a413930-2852-43fc-a79c-dc6758556af7?q=vreede&has-link=yes&c=0&p=5

Vreede, N. (2018b). *Reach Out for Stability - One Pager.* The Hague University of Applied Sciences.

Wheelchair and Cushion Standards Group - University of Pittsburgh. (2024, February 25). *Translating Standards into Strategies.* Https://Wheelchairstandards.Com/.