White Paper

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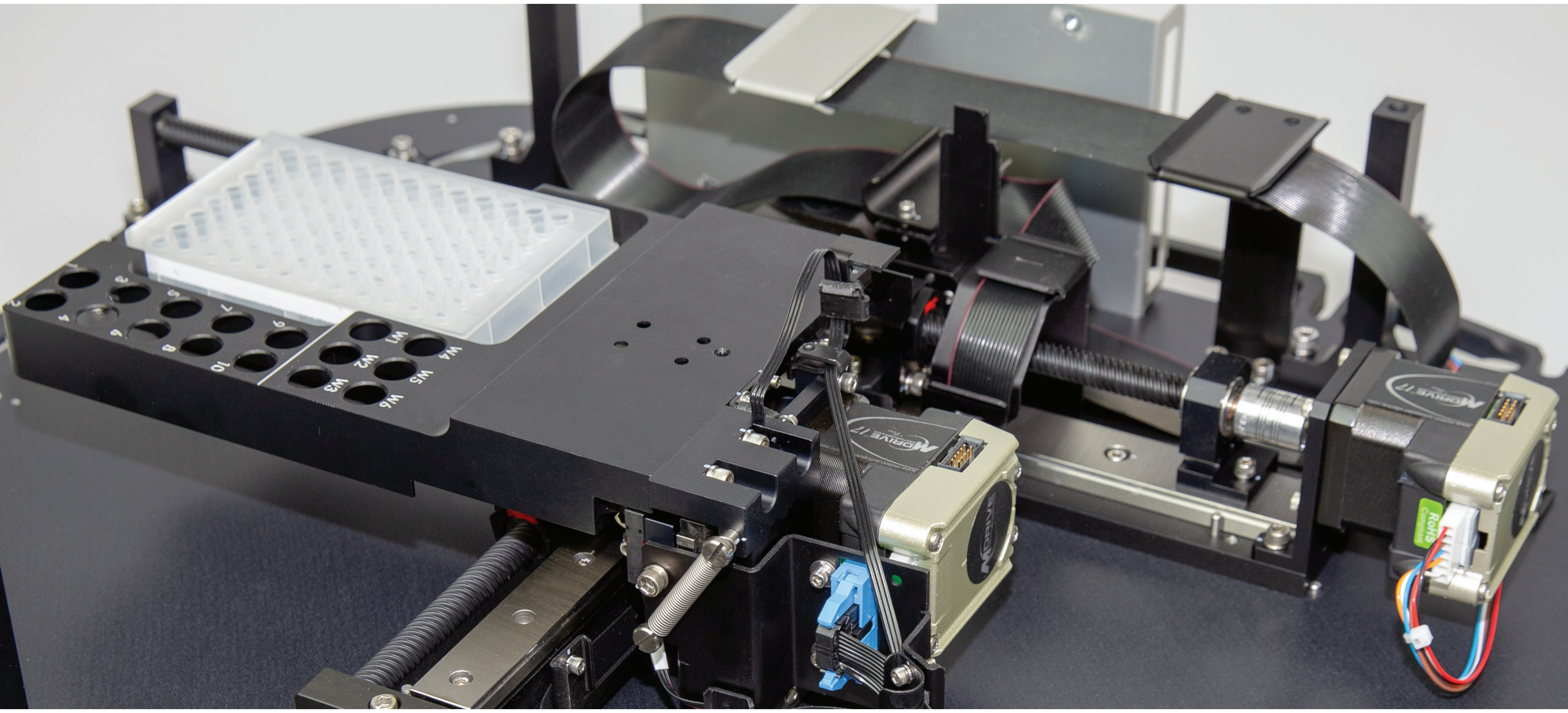
How to Select the Ideal Linear Bearing for Your Medical Application



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Executive Summary

In linear motion systems, performance starts with the bearing system. Engineers often underestimate the importance of these components and leave their design until last. Such delays can be a major problem, particularly if the machine layout doesn't include space for a bearing that can deliver the accuracy, resolution, and repeatability required for the application. Designers need to understand their degrees of design freedom and take into account all trade-offs before specifying a bearing. In this white paper, we will review what medical and biomedical device designers need to know about their application, their design, and their bearing options in order to make the optimal choice for their performance requirements and budget.

Bearing Basics

A linear bearing consists of a carriage, which carries the load, and a linear rail. A variety of rail shapes are available, ranging from plain carriages that slide on round rails to carriages with crossed rollers that move on precision square rails. Round rails and square rails are the most common choices and each involves trade-offs. Round rails are economical and forgiving of misalignment but have lower stiffness and accuracy. Square rails deliver better stiffness and accuracy but have very high requirements for mounting accuracy, including flatness and parallelism. For demanding medical applications, square rails tend to be the most common choice.

Some of the key factors to take into account when choosing a bearing include size (cross-section), accuracy, stiffness, preload, and cost. Stiffness refers to a bearing's ability to resist deflection. A bearing nominally has a certain amount of clearance between the carriage and the rail. When the load is applied, the rolling elements will compress, causing the position of the load to deflect from its intended position. This deflection can be considered an offset that remains constant over the length of travel. Depending on performance requirements, however, too much deflection may be unacceptable. The solution is to reduce deflection by applying a preload.

Applying a preload to a bearing involves inserting balls or rollers that are slightly larger than the available space, often, by a matter of microns. When the balls/rollers are installed in the race, they undergo compression – essentially, they are pre-compressed before the load is ever applied. This pre-compression limits the amount of additional deformation that takes place when the load is added. That, in turn, reduces the deflection of the bearing and increases the stiffness (see figure 1).

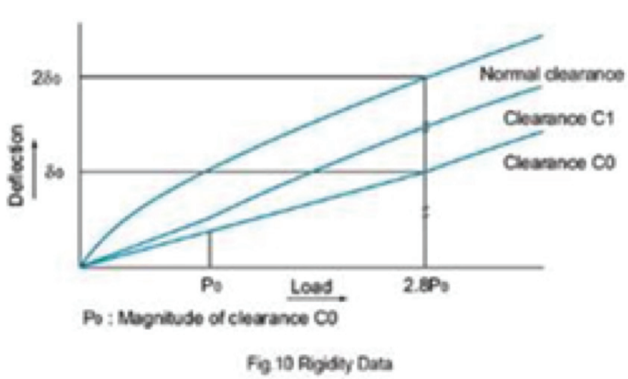


Figure 1:

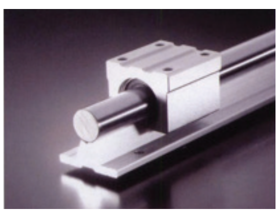
Plot of deflection as a function of load compares stage deflection with normal clearance (top), light preload (C1, middle), and medium preload (see two, bottom).

(Courtesy of THK).

The trade-off for increasing preload is greater rolling resistance. The trick is to find a preload that enables the bearing to resist deflection while remaining small enough to preserve smooth motion. A good starting point is to begin with a line to line preload in which the balls just fit the allotted space, leaving negligible clearance but also applying no preload. This can work well for light loads. For heavier loads or moment loads, additional preload might be necessary to prevent deflection.

Another consideration to keep in mind is that, depending on the mounting tolerances of the system, the act of assembling the system may apply preload. In this case, it might be appropriate to add some clearance in the bearing to ensure smooth motion. In many cases, it comes down to experience, so be sure to consult with linear bearing experts for assistance.

Table 1. Performance comparison between round and square rails

Guide Shape		Cross-section	Stiffness	Accuracy	Preload	Cost
Round rail		★★	★★	★★	★★	★★★★
Two-row square rail, ball		★★★★★	★★★	★★★★	★★★	★★★
Four-row square rail, ball		★★★★	★★★★	★★★★★	★★★★	★★★
Four-row square rail, roller		★★★★	★★★★★	★★★★★	★★★★★	★★
Four-row square rail, ball (wide rail)		★★★	★★★★	★★★★★	★★★★	★★★

Rolling Elements

Precision bearings use rolling elements to minimize friction. The most common load-bearing elements are balls and cylindrical rollers.

In ball bearings, the balls are enclosed between the rail and a curved surface ground into the carriage known as a raceway. The balls are laid out in one or more rows (per side of the bearing) and recirculate as the carriage travels, giving the bearing theoretically infinite stroke length (see figure 2).

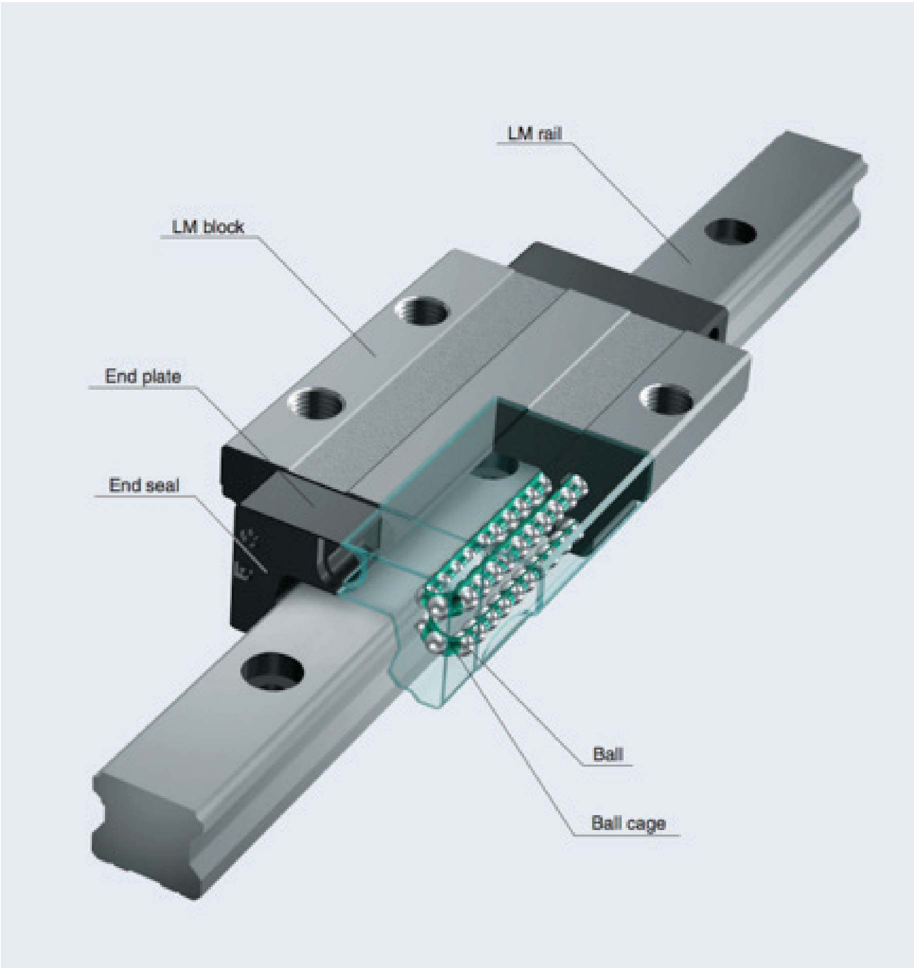


Figure 2:
In ball-type linear bearings, the balls recirculate, for theoretically infinite travel. The balls are arranged in one or more rows to distribute the load and minimize friction.

(Courtesy of THK)

Ball-type linear bearings can be specified with a ball cage, or separator. Ball cages are polymer structures molded to closely fit the surface of the balls. They separate the balls and ensure orderly movement for better high-speed performance. Ball cages minimize metal-to-metal contact, reducing wear and noise. They also do a better job of retaining grease, which increases bearing lifetime and maintenance intervals (see figure 3).

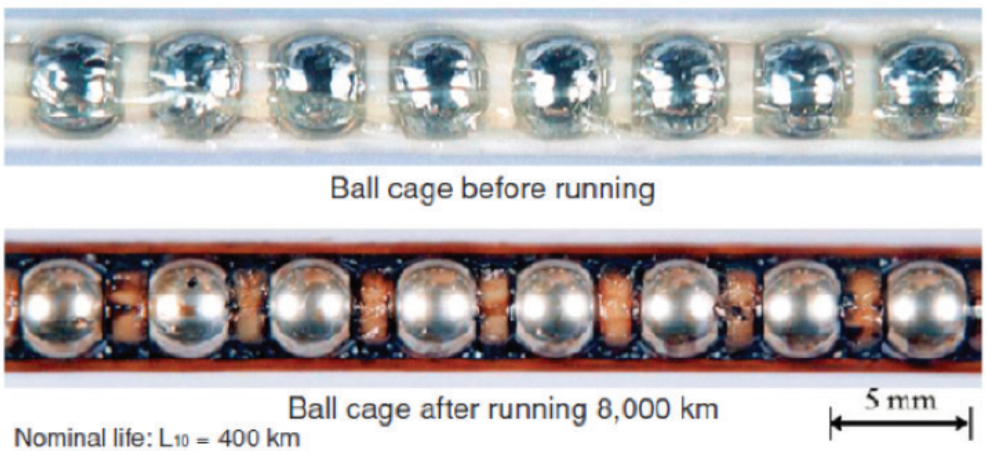


Figure 3:
In an extended durability test of THK's LM guide, a significant amount of the grease originally packed into the bearing (top) remains after the device runs 8000 km (bottom).

(Courtesy of THK)

Users should be cautious when changing greases because trace amounts are easily retained by the cages. Other than that, there are few drawbacks to the technology. Ball cages add minimal cost to a bearing. When properly specified, they are also robust. The savings they offer in terms of prolonging bearing lifetime and reducing maintenance more than justifies the additional outlay.

Crossed-roller bearings support the load on cylindrical rollers position orthogonally to one another (see figure 4 next page). Rollers have a line contact rather than a circular contact. As a result, for a given diameter, a roller has a larger contact area than a ball, giving it a higher load capacity.

Figure 4:
The cylindrical rollers in a crossed-roller bearing provide a larger contact area for increased loadbearing capability and higher stiffness.

(Courtesy of THK)

As with ball-type linear bearings, roller bearings are available in recirculating and non-recirculating versions. Recirculating designs offer near infinite travel. The trade-off is significantly higher cost, however. The mounting tolerances are also tighter than for ball-type bearings. Any deviation of the mounting surface or installation procedure can introduce significant amounts of friction. They also tend to be a bit higher than the nonrecirculating counterparts.

Nonrecirculating roller bearings have limited stroke lengths, typically a meter or less. They have a smaller cross-section than the recirculating types, which makes them effective for applications requiring both a low profile and high stiffness. In the case of a multiaxis patient bed, we chose a nonrecirculating crossed-roller bearing for the lateral axis because it provided good stiffness and a lower profile for our space-constrained application.

Nonrecirculating crossed-roller bearings do have their challenges. With recirculating types, preload is set at the factory. For nonrecirculating bearings, the user has to apply the preload during installation using setscrews. This can be more challenging than users expect. At Motion Solutions, our engineers and technicians have years of experience with crossed-roller bearings. We work closely with our customers to help them develop an optimum solution.

Process of Selection

Step #1: What are the performance parameters?

Positioning accuracy is primarily determined by the drive system, which includes motor, drive, feedback, and controller. The linear bearing does not determine accuracy, although it can contribute somewhat to error. The two primary error sources in a linear bearing are:

- Running parallelism: Bearings have some deviation from absolute straightness as a result of machining and assembly tolerances, and mounting errors.
- Deflection: Excess clearance in the bearing can cause the load to deflect from intended position.

For very demanding performance requirements, start by properly specifying the bearing to handle the load on an axis-by-axis level. Choose an appropriate preload. Higher preloads reduce deflection under load but increase running friction. Lower (or no) preloads can work for light loads that need smooth motion.

Duty cycle is another key consideration. Are you going to do thousands or millions of cycles? Will there be a preventative maintenance cycle? Lower duty cycles may allow the use of low-cost, non-cage, single-row ball-type bearings bearing or even ball bushings. Higher duty cycles should use caged-ball type bearings and may require the addition of a self-lubricator.

Step #2: What is the machine layout?

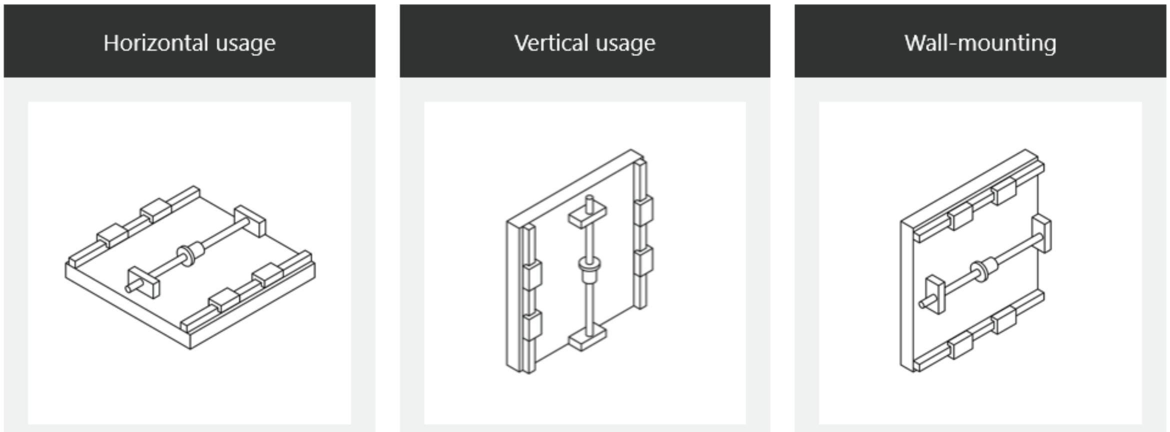
The layout determines the number of axes of motion, their orientation, the forces imposed, and any packaging constraints. This information makes it possible to determine the number of rails involved and calculate the magnitude and type of load on each rail. From there, we can choose the type of rail. Now, we can perform a detailed analysis to determine what bearings–if any–can both serve the layout and deliver the performance required.

Be sure to take into account not just the layout but the orientation. A Cartesian system hanging on the wall will be exposed to significantly different forces than one laid flat (see figure 5 next page).

Figure 5:

The orientation of the system can significantly change the forces involved.

(Courtesy of THK)



Step #3: What are the loads?

Capital equipment purchased for the medical market is expected to last five to seven years. Proper sizing of the bearing is essential to achieving lifetime specifications. Loads can be broken into static and dynamic loads.

Static requirements

Determine the number of axes in the system and evaluate the loads for each axis (see figure 6). Start with the load type:

- Axial (thrust load): The load applies a force in the direction of travel.
- Radial load: The load applies a force orthogonal to the direction of travel.
- Moment load: The load applies a force at a distance, or torque around the axis. The moment direction may be described as Ma (pitching), Mb (yaw), Mc (rolling).

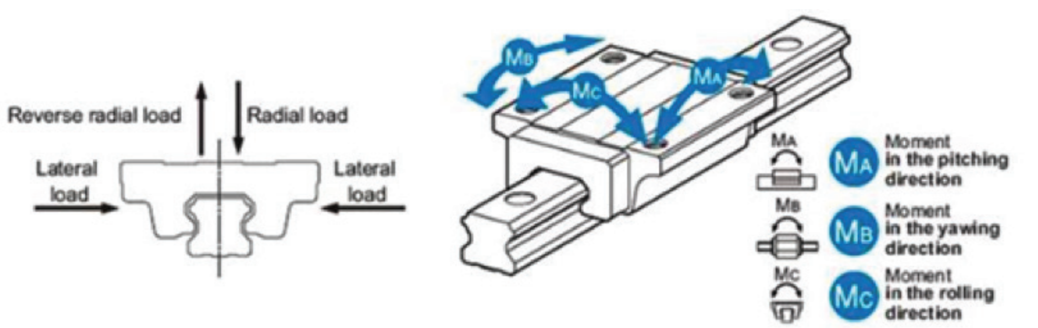


Figure 6:

The loads acting on each axis include radial loads, axial loads, lateral loads, and moment loads.

(Courtesy of THK)

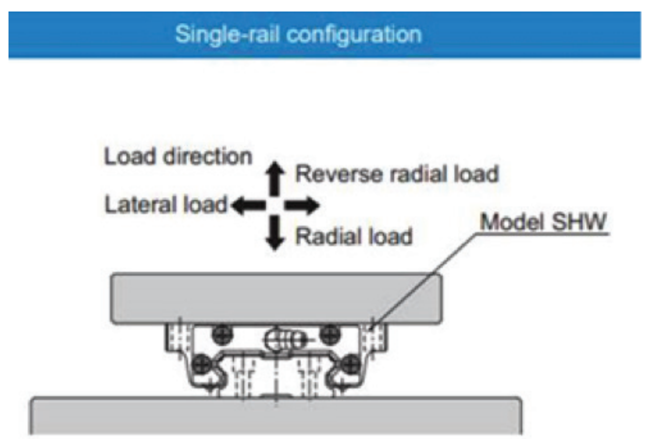
Calculate the force vectors (magnitude and direction) on an axis-by-axis basis and also for the assembly as a whole. Be sure to take into account both the applied load and any force applied by the components of the machine itself. A patient bed, for example, might involve two or three stacked axes, so that the load on the lower axis includes not only the patient but the weight of the components that form the axes above. Start at the applied load and work through the stack.

Dynamic requirements

Dynamic loads include the static load of the mass, plus dynamic loads due to acceleration. In some cases, the machine itself may apply a load. Loads interact with one another. This particularly holds for complex motion stages, for which the dynamic forces change rapidly as various components reposition.

Again, start at the top layer and work your way through the stack. Try to keep the top layer as light as possible because the forces will be summed. This information will help determine the best choice of bearing.

Ultimately, specifying the bearing involves trade-offs. A single-rail bearing might work well for a small, light load, even when it has an applied moment load. Heavier loads, particularly heavy moment loads, typically call for dual-rail systems (see figure 7). Widening the distance between rails reduces the reaction forces on the bearings, enabling them to better handle the applied moment.



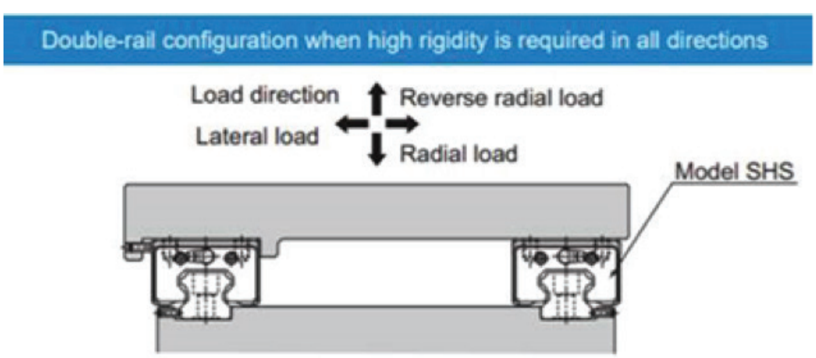


Figure 7:
Single-rail bearings work well for light loads, even with applied moments. For heavier loads, particularly heavy moment loads, the dual-rail configuration reduces the reaction forces on the bearing

If the load is centered on the carriage, there is a greater possibility that a single-axis system will be enough. Wide square-rail designs increase the distance between the raceways, once again lowering the reaction forces and increasing the moment load that the single-rail bearing can support compared to conventional square-rail bearings. Perform a detailed mechanical analysis to gain the best understanding of system requirements. Be sure to take into account duty cycle when you are calculating bearing life.

The process above can be difficult and time-consuming. To simplify matters, most bearing manufacturers offer online bearing lifetime calculators, such as this one. The designer just needs to input required parameters and the tool does the rest.

Step #4: What are the environmental considerations?

Medical applications have very long lifetime requirements. Certain environmental factors can significantly impact performance and lifetime.

- Will the bearing be exposed to corrosive substances or high humidity? Although medical facilities tend to be climate controlled, that may not be the case for rural locations. Equipment may also be exposed to high humidity during transport. Look for corrosion-resistant materials (e.g. stainless steel and specialty coatings).
- Is the application designed for cleanroom or vacuum environments? Specify clean-room or vacuum grease as appropriate.

Bearing Selection Case Studies

Now that we've reviewed the most important considerations for selecting a linear bearing, let's illustrate the process using four common medical and life sciences examples.

Application #1: Blood Analyzer

In a blood analyzer, the motion system moves cassettes of sample holders from intake to the active area. There, motion axes will position the cassettes under an array of pipettes for sample distribution or under the measurement probes for spectroscopic analysis.

Table 2. Requirements for blood analyzer

	X-axis	Y-axis	Z-axis
Function	Positioning sample holder	Positioning sample holder	Positioning pipettes/ measurement probes
Loads	• Light • Some moment load — stage moves sampel tray from intake to instrument	• Light • Some moment load — stage moves sampel tray from intake to instrument	• Light • High duty cycle

SYSTEM LEVEL	
Duty cycle	Can be very high
Environmental	High humidity, corrosive materials

Bearing choice:

The ideal choice of bearing for a blood analyzer requires a balance among factors like cost, lifetime, form factor, stiffness, and running parallelism (linear accuracy). Plane bearings (sliding contact) are economical but they degrade rapidly in performance. Because they lack rolling elements, they require a certain amount of clearance to operate. If they are preloaded to restrict that clearance, they will begin to generate heat rapidly, even at low speeds. Even without preload, they still cause excess wear and particulation. Recirculating ball-type linear guides are better solutions. They provide longer life and better, more consistent performance in exchange for only a modest cost increase.

Table 3. Bearing choice for blood analyzer

	X-axis	Y-axis	Z-axis
Type	Recirculating ball-type linear guide	Recirculating ball-type linear guide	Recirculating ball-type linear guide
Load type	Light, overhung moment load	Light, overhung moment load	Light, centered
Number of rows	Two	Two	Two
Rail type	Square	Square	Square
Number of rails	One wide-series bearing	One wide-series bearing	Standard single rail
Number of blocks	1	1	1
Preload	Light	Light	Light
Rail accuracy	Normal	Normal	Normal

	SYSTEM LEVEL
Materials	Stainless bearings and screws
Special	Specialty greases to minimize dusting

In particular, the use of the single-rail wide-series bearing lets the system accommodate the overhung moment loads while minimizing cost and mounting complexity.

Application #2: Microtome for thin sectioning tissue samples

Microtomes are used to slice tissue samples into thin sections for analysis. The tissue is fixed in paraffin and placed in a sample mount that is raised and lowered over a very sharp blade to shave off slices a few microns thick. Z-axis motion must be highly smooth and rigid to prevent sample distortion. Even though cutting motion is 1D, samples also must be tightly constrained along the horizontal axis to prevent thickness variations that could be misinterpreted as tissue abnormalities.

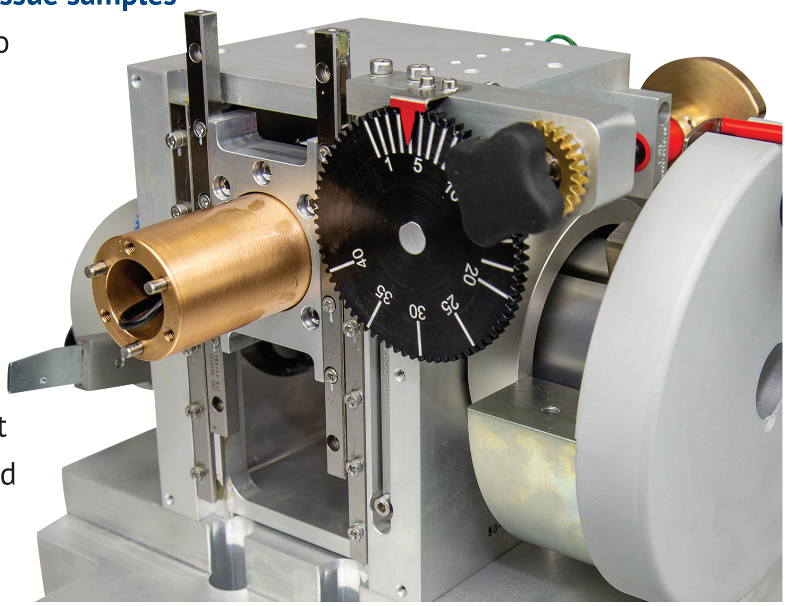


Table 4. Requirements for microtome

	X-axis	Z-axis
Function	Prevents lateral motion during thin sectioning	Raises and lowers sample holder across blade
Loads	• Light	• Light • Variable resistance – tissue samples range from organs to tendons and ligaments
Friction	Low, motion must be very smooth	Low, motion must be very smooth
Special	Very stiff – thickness variations of sample could be misread as tissue abnormalities	
	SYSTEM LEVEL	
Duty cycles	Very high	
Environmental	Exposed to contamination and corrosive cleaners	

Bearing choice:

Although the operating speeds of microtomes are low, duty cycles can range from a few times a week for a research facility to 24/7 at a commercial laboratory. The bearings need maximum lifetime as well as minimum deflection. Along the X axis, a plane bearing is the best choice. Plane bearings maximize contact surface area for highest possible stiffness (see table 1).

Along the Z axis, a crossed-roller bearing provides a good balance between high stiffness and smooth motion.

Table 5. Bearing choice for microtome

	X-axis	Z-axis
Type	Custom plane bearing • Bronze shaft in hard anodized aluminum bore • Maximum surface area for high stiffness	Crossed-roller bearing • Line contact for high stiffness • Large surface area to maximize load capacity
Rail type	Round	
Number of rows	N/A	Two
Rail type	N/A	Square
Number of rails	N/A	Four
Number of blocks	N/A	One moving carriage
Preload?	N/A	Yes
Rail accuracy	Normal	Normal
	SYSTEM LEVEL	
Material	Stainless steel or special plating	

Application #3: Patient bed for radiotherapy machine

Patient beds for the latest generation of radiotherapy machines may need to move during treatment. Patient positioning has to be both accurate and high-resolution to avoid exposing healthy tissue to ionizing radiation.

Bearing choice:

To meet specifications, the mechanical design needed to minimize deflection throughout full range of travel. We began by designing the Z-axis, because it was most challenging. When Y-axis load is at

Table 6. Requirements for patient bed

	X-axis	Y-axis	Z-axis
Function	Short stroke, side-to-side less than 10 cm of travel	Long stroke, moving in and out of machine	Very rigid, hold load with minimum deflection over full range of Y-axis travel
Loads	Typically heavy, especially if bariatric	Frequently high moment loads; Lower axes must support axes above	Changes during Y-axis travel from evenly distributed to completely cantilevered with high moment load
SYSTEM LEVEL			
Duty cycle	low		
Audible noise	Low – patient-facing appication		
Environmental concerns	Corrosion resistance; Radiation exposure		

minimum travel, the bearings are in compression. When Y-axis travel is at maximum, the inboard bearing is in compression while the outboard bearing is in tension. A roller bearing would have provided greater stiffness in a smaller package but at higher cost. Since cost control is a concern but size/weight are not, we chose an oversized ball type linear bearing with the rails set as widely as possible. The rails were coated with Armolloy TDC (thin dense chrome) for corrosion resistance.

Table 7. Bearing choice for patient bed

	X-axis	Y-axis	Z-axis	Pitch axis	Yaw axis
Type	Crossed-roller bearing • Minimize overall stack • Short range of travel so cost penalty is minimum	• Recirculating ball bearing	Recirculating ball bearing • Minimize height	Rotary	
Number of rows	1	4	4		4
Rail type	Crossed roller	45° contact angles, equal load rating in all directions	45° contact angles, equal load rating in all directions		Curved square rail – more compact than tradition thin section bearing
Number of rails	Two inner, two outer	2	2		Two arced sections
Number of blocks	N/A	3	4		Three per arced section
Preload?	Set upon installation	Light	Yes		Light
	SYSTEM LEVEL				
Duty cycles	Low				
Audible noise	Low – patient-facing application				
Material	Stainless steel with specialty plating; Radiolucent				

Conclusion

Choosing the best bearing for your application begins with defining the requirements of the application upfront. Analyze that information in the context of the trade-offs discussed above to choose two or three of the most promising configurations for further exploration. Consider all details such as preload, cleanliness, seals, material requirements, lubrication, duty cycle, etc. Determine your priorities and then begin making trade-offs. Don't forget that for sufficient volumes, customization is always a possibility.

For More Information

Learn more about how Motion Solutions can collaborate with you on your next project at www.motionsolutions.com or by calling 949-586-7442.

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